FORUM

Integrating Biological and Chemical Controls in Decision Making: European Corn Borer (Lepidoptera: Crambidae) Control in Sweet Corn as an Example

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ABSTRACT As growers switch to transgenic crops and selective insecticides that are less toxic to natural enemies, natural enemies can become more important in agricultural pest management. Current decision-making guides are generally based on pest abundance and do not address pest and natural enemy toxicity differences among insecticides or the impact of natural enemies on pest survival. A refined approach to making pest management decisions is to include the impact of natural enemies and insecticides, thereby better integrating biological and chemical control. The result of this integration is a dynamic threshold that varies for each product and the level of biological control expected. To demonstrate the significance of conserved biological control in commercial production, a decision-making guide was developed that evaluates control options for European corn borer, *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae), in sweet corn, *Zea mays* L., where the primary natural enemies are generalist predators. Management options are λ-cyhalothrin (broad-spectrum insecticide), spinosad (selective insecticide), *Trichogramma ostriniae* (Peng & Chen) (Hymenoptera: Trichogrammatidae) (parasitoid), and *Bacillus thuringiensis* (Bt) sweet corn (transgenic variety). The key factors influencing thresholds for all treatments are the intended market, predator populations, and the presence of alternative foods for the predators. Treatment cost is the primary factor separating the threshold for each treatment within a common scenario, with the lowest cost treatment having the lowest pest threshold. However, when the impact of a treatment on natural enemies is projected over the 3-wk control period, the impact of the treatment on predators becomes the key factor in determining the threshold, so the lowest thresholds are for broad-spectrum treatments, whereas selective products can have thresholds >6 times higher by the third week. This decision guide can serve as a framework to help focus future integrated pest management research and to aid in the selection of pest management tools.

KEY WORDS model, insecticides, biological control, IPM, *Bacillus thuringiensis*

Economic injury levels (EIL) and their related economic thresholds have been developed for pests in many cropping systems. The EIL is defined as "the lowest population density that will cause economic damage" (Pedigo et al. 1986). The EIL does not forecast pest density, so most fluctuation in the EIL for a given pest–crop combination is due to economic changes (Brown 1997), namely, crop value and control costs. The economic threshold is the predictive form of the EIL, being "the pest density or plant injury level corresponding to the latest possible date for which a control tactic could be implemented to prevent economic damage" (Pedigo et al. 1986). Because the economic threshold is determined when controls can be applied, for some pests such as miners, borers, and soil-dwelling insects, the economic threshold needs to be determined weeks before economic injury will occur. In these cases, mortality from biological and weather factors (e.g., natural enemies, rain, and temperature) in the period between determining the economic threshold and realizing economic damage strongly influence the true economic threshold. Therefore, the true economic threshold is dynamic, moving up or down with changes in biological and natural mortality in the period between economic threshold determination and economic injury realization. However, because these values are generally unknown or unpredictable, a common approach to pest management has been to use a relatively constant economic threshold, limiting variation to different periods of crop maturity (and sometimes crop value or control costs), and using fixed values for other factors (Brown 1997). Although this economic threshold is not perfect, many growers and crop consultants now base their management decisions on these static economic thresholds. The result is often a reduction in

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pesticide use compared with regularly scheduled sprays (Shelton 1986, Lamp et al. 1991, Hoffmann et al. 1995, Sikora et al. 2002).

Because most thresholds were determined from research using broad-spectrum insecticides, they assume very low levels of biological control between pesticide application and economic injury. With the use of more selective insecticides, biological control levels during this time period increase (Johnson and Tabashnik 1999), so the use of thresholds developed with broad-spectrum insecticides will likely result in the application of selective insecticides when not warranted (Brown 1997). The results are less than optimum economic returns to the grower and unneeded insecticides in the environment.

To deal with biological and weather factors, ecological models have been developed to improve our understanding of population dynamics (Menke and Greene 1976, Onstad 1988, Coll and Izraylevich 1997). In some cases, these models also have included the impact of various management practices (Onstad and Guse 1999). However, these ecological models can seldom be used as decision-making guides. With the increased availability of computer technology and the increasing importance of biological control in pest management, decision-making guides that integrate pest mortality from chemical, biological, and abiotic factors need to be developed. These guides should build on the familiar concepts of EILs and economic thresholds, and include the dynamic impact of biological control agents on the economic threshold. Furthermore they should include the variable impact of control options on the biological control agents. There have been numerous efforts to incorporate some of these factors into economic thresholds. For example, the economic value society places on environmental stewardship has been incorporated into economic thresholds (Higley and Wintersteen 1992, Kovach et al. 1992, Pedigo and Higley 1992), mortality factors have been incorporated into economic thresholds by using life tables and stage-specific monitoring for pests with discrete generations (Ostlie and Pedigo 1987, Barrigossi et al. 2003), and "inaction thresholds" have been established where natural enemy densities are sufficient to maintain pest densities below the EIL (Sterling 1984). All of these approaches have moved pest management decisions toward their true dynamic nature, while trying to preserve the simplicity of the economic threshold concept. We likewise propose to use the economic threshold concept while recognizing the dynamic nature of many of the variables that determine the economic threshold.

In our approach, we limit the scope of our decision-making guide to the direct economic impacts of biological and chemical control agents, namely, their contribution to the control of pests and their interaction with other control agents. This pest management approach can be readily understood and varies widely between management alternatives, and yet we are aware of only one published economic threshold guide that includes both the selectivity of pesticides and the contribution of beneficial organisms (Hamilton et al. 2004). With the increasing selectivity of pesticides and the introduction of selective insecticidal transgenic crops, these interactions have become more significant and need to be considered when comparing management options.

Developing a decision guide that includes the impact of biological control requires data on the impact of the biological control agents on the target pests, impacts of the management options on the biological control agents and pests, interactions of biological control agents with each other, and how these factors change over crop maturity and weather conditions. In some situations natural enemy and pest population dynamics may need to be considered. However, in many agricultural situations, field monitoring is frequent enough that static populations can be assumed for the period between monitoring events. For generalist natural enemies, impact on the target pest also may be dependent on the availability of other hosts or prey. In most cropping systems, a complete set of these data are not readily available to develop such a decision guide. Although this limits the number of situations where this type of decision guide can be easily developed, the need for this type of decision guide can help focus research on areas that need more attention. To illustrate how such a decision guide could work, a decision guide has been developed for controlling European corn borer, *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae), in sweet corn, *Zea mays* L. This system was chosen due to the extensive literature available, the existence of several traditional decision guides (Flood et al. 1995, Dively 1996, Reiners et al. 2004), the national importance of this pest, the substantial lag time between determining the economic threshold and the EIL, and the availability of selective products for controlling this pest.

Existing decision guides for *O. nubilalis* in sweet corn are based on pest density, crop value, and crop maturity (Flood et al. 1995, Dively 1996, Mason et al. 1996, Reiners et al. 2004). Although these guides describe several long-range preventative control methods, their focus is on short-term control options, namely, insecticides. Therefore, the decisions to be made are which insecticide product to use and when it should be applied. Our proposed decision guide follows a similar approach. However, we also include options that need to be implemented earlier in the season (transgenic varieties expressing *Bacillus thuringiensis* [Bt] toxins, parasitoid release) to enable a direct comparison of these practices with insecticides for long-term planning purposes.

An unstated assumption of existing guides is that biological control is not a significant factor in *O. nubilalis* control. Although this may have been generally true after the first application of a broad-spectrum insecticide, this is no longer a valid assumption for the newer, more selective products (Murray and Lloyd 1997, Duffie et al. 1998, Tillman et al. 1998, Studebaker and Kring 1999, Musser and Shelton 2003a). These newer products are not as toxic to natural enemies, so biological and chemical control tactics can provide control simultaneously. In the sweet corn system,

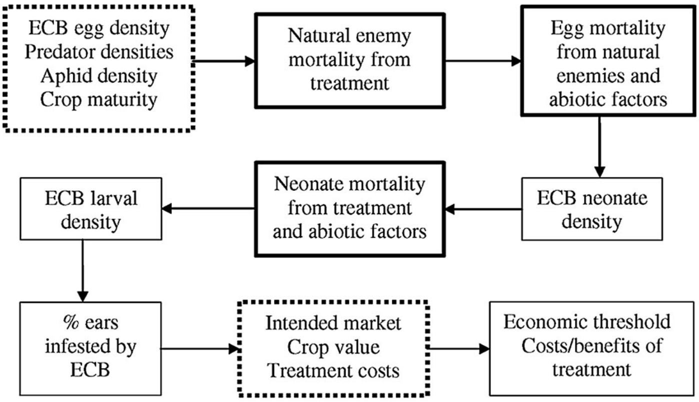

Fig. 1. Flow chart of single point-in-time model. Boxes with bold dashed lines are values required from the user. Boxes with bold solid lines are values for processes determined from experimental data. Boxes with regular solid lines are results. ECB, European corn borer.

pathogens, parasitoids, and predators all provide some control of *O. nubilalis,* but predators seem to be the most significant natural control agents in the northeastern U.S. (Whitman 1975, Coll and Bottrell 1992, Losey et al. 1992, Mason et al. 1994, Musser et al. 2004). There also has been interest and progress in augmentative releases of *Trichogramma ostriniae* (Peng & Chen) (Hymenoptera: Trichogrammatidae) to control *O. nubilalis* (Kuhar et al. 2002, Wright et al. 2002), so naturally occurring predators and a single release of *T. ostriniae* are the primary beneficial organisms included in this decision-making guide.

In New York, most fresh market sweet corn is sprayed between 2 and 4 times (USDA–NASS 2003) during the 3–4-wk period between tassel emergence and harvest to control *O. nubilalis.* Sweet corn used for processing has a lower economic value than fresh market sweet corn, and some tip damage can be removed during processing, so only one or two insecticide applications are typically made on processing sweet corn (USDA–NASS 2003).

Materials and Methods

Overview. This decision-making guide is built on a Microsoft Excel 2003 spreadsheet. It contains two models: a single point-in-time model (*Appendix* A) and a 3-wk model. The flow chart in Fig. 1 shows the linear logic of the single point-in-time model that was built on empirical data collected in numerous studies in New York plus values obtained from field corn and sweet corn literature. The 3-wk model links three single point-in-time models together using population dynamic assumptions that result in natural enemy population densities comparable to observed densities (Fig. 2) (Musser and Shelton 2003b, Musser et al. 2004). The single point-in-time model was designed to determine economic thresholds and evaluate treatment options where sampling data are available, whereas the 3-wk model was designed to compare longer term effects of management decisions. Like other sweet corn decision guides, this guide begins with *O. nubilalis* density. It then estimates predator densities adjusted for mortality from each management option. Egg predation is estimated using pest and predator densities and egg consumption rates by the major predators after consideration of pollen and aphid availability (Musser and Shelton 2003c). The pest control from parasitoids (Kuhar et al. 2002), insecticides and transgenic varieties (Musser and Shelton 2003a) are then estimated, leading to an estimate of expected damage to the crop from *O. nubilalis* for each management option.

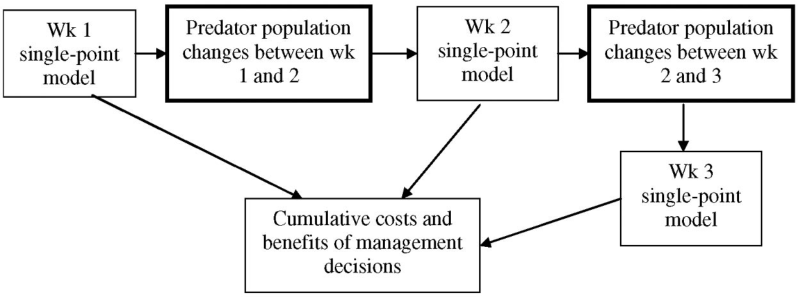

Fig. 2. Flow chart of 3-wk model. Boxes with bold lines are values for processes based on observations.

Table 1. Values of predator densities and factors used to estimate predation in this decision-making guide

Predator	Predator densities used in Table 3 scenarios, no./40 plants			Visual count correction[a]	Maximum predation[b] egg masses/predator/d	Alternative food source adjustments						
						Crop maturity (pollen)[c]				% plants with >50 aphids		
	High	Average	Low			Late whorl	Tassel	Fresh silk	Brown silk	Low <10	Med. 10–30	High >30
C. maculata adult	12.0	2.3	0.7	1.39	0.71	1.0	0.57	0.14	0.57	1.0	0.73	0.46
C. maculata large larva	42.8	7.7	2.5	1.51	0.95	1.0	0.61	0.22	0.61	1.0	0.81	0.62
H. axyridis adult	11.2	0.9	0.6	1.13	0.22	1.0	0.75	0.50	0.75	1.0	0.70	0.39
H. axyridis large larva	33.2	3.4	1.8	1.58	0.41	1.0	0.77	0.54	0.77	1.0	0.74	0.48
O. insidiosus adult	39.6	11.0	2.5	5.44	0.07	1.0	0.76	0.52	0.76	1.0	0.65	0.30
O. insidiosus nymph	16.8	3.3	1.0	12.34	0.06	1.0	0.67	0.33	0.67	1.0	0.54	0.07

[a] Ratio of actual density to visual counts (Musser et al. 2004).

[b] Average *O. nubilalis* egg masses consumed per d when no other food sources are available (Musser and Shelton 2003c).

[c] Proportion of *O. nubilalis* eggs consumed based on the availability of pollen. Values are from an experiment with no pollen (late whorl) and pollen (fresh silk). Tassel and brown silk values are the average of the late whorl and fresh silk values (Musser and Shelton 2003c).

[d] Proportion of *O. nubilalis* eggs consumed based on the availability of aphids. Values are from an experiment with no aphids (low) and aphids (high). The medium aphid value is the average of the low and high aphid values (Musser and Shelton 2003c).

Pest Pressure. Blacklight trapping of adults is frequently recommended as the best monitoring tool to estimate *O. nubilalis* pressure (Dively 1996, Mason et al. 1996), but there is not a strong connection between blacklight trap counts and egg density (Showers et al. 1974, Ngollo et al. 2000). Although egg mass sampling is more time-consuming than blacklight traps, a more accurate prediction of *O. nubilalis* damage can be obtained from egg mass sampling. Current recommendations in New York are primarily based on larval and egg mass counts (Reiners et al. 2004). Two egg masses per 40 plants is the threshold used for treatment in processing sweet corn with a goal of keeping ear damage below 5%. An *O. nubilalis* egg mass typically contains 15–30 eggs (Mason et al. 1996), and the larvae can infest all parts of the plant, including the stalk, leaf midribs, and ear. We base our calculations on an average of 17 eggs per egg mass and assume that 10% of eggs never hatch (Kuhar et al. 2002). Estimates of overall larval mortality during the first 4–5 d (before ear feeding is likely) range from 52 to 83% with the exception of 1 yr of one study reporting only 29% mortality (Showers et al. 1978, Siegel et al. 1987, Lee 1988, Ross and Ostlie 1990, Coll and Bottrell 1992, Kuhar et al. 2002), with most of the mortality occurring within the first 48 h after egg hatch. We use a conservative 52% larval mortality rate in our decision guide. Shelton et al. (1986) found <20% of total larvae in the ear before silk stage, but up to 50% of larvae boring in the ear from silk stage until harvest. Similarly, Wright et al. (2002) recorded 25–35% of *O. nubilalis* feeding in the ear. In this guide, we assume that 40% of larval tunneling will be in the ear at all reproductive crop stages. Each larva that survives the first 48 h is assumed to make 1.5 tunnels conservatively based on data from Wright et al. (2002) and Ross and Ostlie (1990). Because 90% of larvae stay within 50 cm of the plant on which they hatched with ≈50% never leaving the plant on which they hatched (Ross and Ostlie 1990), we assumed for this guide that a maximum of five ears of sweet corn (original host plant and two adjacent plants on each side) could be infested from each egg mass. Due to the clustered distribution of *O. nubilalis* larvae, the number of ears damaged per egg mass does not increase linearly with increased larval survival. To convert the number of ear cavities to ears damaged we assumed that each ear cavity occurs in a separate ear up to 2.5 ear cavities per egg mass. Above that density, additional ears are damaged at a declining rate until five ears are damaged from a density of 10 cavities per egg mass. Density-dependent mortality of *O. nubilalis* has only been observed at densities >3.5 egg masses per plant (Onstad 1988, Labatte et al. 1997), a density exceeding densities in the northeastern United States (Shelton et al. 1986, Spangler and Calvin 2000, Spangler et al. 2003), so *O. nubilalis* mortality is assumed to be density-independent in this guide.

Egg Predation. Overall *O. nubilalis* egg predation is a function of predator population sizes and the amount of egg predation by each predator population. The primary predators in New York are *Coleomegilla maculata* De Geer, *Harmonia axyridis* (Pallas) (Coleoptera: Coccinellidae) and *Orius insidiosus* (Say) (Hemiptera: Anthocoridae), all of which can be sampled using a visual count (Musser et al. 2004). Therefore, this guide is based on 40-plant visual counts but can be readily adjusted for any plant sample size. Based on comparisons between visual counts and a destructive sampling method, all predator species are not seen equally well (Musser et al. 2004). This seems to be a function of size and color with large, brightly colored coccinellid adults most visible, and small, dark green *O. insidiosus* nymphs least visible. As small coccinellid larvae consume very little and are difficult to find and identify, only large larvae are included in the visual count. An adjustment is made to convert visual counts into actual population densities based on destructive counts (Table 1) (Musser et al. 2004).

Estimated population densities are multiplied by the maximum individual predation rates observed for each species when no other food sources are available (Musser and Shelton 2003c) to estimate maximum population predation rates. These predation rates are then adjusted for the presence of corn pollen and aphids, two factors shown to significantly decrease the functional response of generalist predators to *O. nubilalis* eggs (Table 1) (Musser and Shelton 2003c). Values for tassel stage and brown silk stage sweet corn are the average of the late whorl and fresh silk values because there is a small amount of pollen present just before and after the main pollen shed period at fresh silk. Likewise, when 10–30% of the plants have >50 aphids, the predation rate adjustment for aphids is the average from the high aphid and low aphid values, based on the likelihood that some predators will find and feed on aphids, but others will never encounter aphids at this density. When >30% of plants have >50 aphids, it is assumed that all predators will encounter aphids, so *O. nubilalis* egg predation is adjusted according to the high aphid values.

Interactions between pollen and aphids are not included in this model. In a laboratory study of the common predators found in New York sweet corn, pollen by aphid interactions were only significant for *C. maculata* adults and *O. insidiosus* nymphs (Musser and Shelton 2003c). In both cases, the predators fed on more *O. nubilalis* eggs when both pollen and aphids were present than predicted based on their predation rates of each food type individually. By omitting the interaction term, a conservative estimate of egg predation is generated for these predators.

Total potential egg predation from the predator complex is estimated by adding up the totals for all the individual populations. The assumption of no interaction between predators has been tested in the field for two coccinellid larval populations, and no negative interactions were detected (Musser and Shelton 2003c, Hoogendoorn and Heimpel 2004). Predicted egg predation is then adjusted from potential egg predation for searching efficiency based on Nicholson and Bailey's model (Nicholson and Bailey 1935). The search efficiency constant $N_{(e)}$ was conservatively set at 0.2 based on field data where predation rates of *O. nubilalis* eggs and predator populations were recorded (Musser and Shelton 2003a,c). The search efficiency in these data ranged from 0.1 to 1.4 with a mean of 0.4. Because 0.2 is the lower 95% confidence interval for the mean search efficiency constant, its use will result in a conservative estimate of the impact of predators on overall control.

Predator Population Dynamics in 3-wk Model. The assumptions made for adult populations of the three major predator species are that the population after 1 wk will equal 80% of the current adult population plus 10% of the larval population of that species. The larval or nymphal population after 1 wk will be three times the current adult population plus 90% of the current immature population. This model approximates the population dynamics of these three predators observed in sweet corn fields in New York during the control window (Musser et al. 2004).

Egg Parasitism. Natural egg parasitism of *O. nubilalis* seldom exceeds 5% throughout the United States (Hudon and LeRoux 1986, Andow and Risch 1987, Jarvis and Guthrie 1987, Wilson and DuRant 1991, Andow 1992). However, recent work has shown that parasitism rates >50% can be regularly achieved by releasing *T. ostriniae* at the rate of 72,000 females per ha, regardless of *O. nubilalis* egg density (Kuhar et al. 2002, Wright et al. 2002). In our decision guide, we assume a 5% parasitism rate when parasitoids are not released and a 50% parasitism rate where *T. ostriniae* are released. This is held constant in the 3-wk model as *T. ostriniae* population dynamics are linked to *O. nubilalis* population dynamics.

Table 2. Insecticide survival values used for natural enemy and *O. nubilalis* populations (predator data in Musser and Shelton 2003c)

Predator	% survival		
	λ-Cyhalothrin	Spinosad	Bt sweet corn
C. maculata adult survival	8	69	100
C. maculata larva survival	0	67	90
H. axyridis adult survival	19	73	88
H. axyridis larva survival	0	68	100
O. insidiosus adult survival	11	100	100
O. insidiosus nymph survival	3	43	100
T. ostriniae survival[a]	60	60	100
O. nubilalis survival (observed)[b]	8	7	0.4
O. nubilalis survival (chemical)[c]	2	4	0.4

[a] Estimate based on reported susceptibility to insecticides as an adult and resistance during other life stages.

[b] Mean values from multiple application insecticide field trials in 2000 and 2001 when applied at the middle of the labeled rate range.

[c] Estimated survival from insecticide alone adjusted from observed survival to account for egg predation rates in the same field trials. For products with a negative impact on predators, chemical survival is lower than observed survival because fewer eggs are killed by biological control agents after the initial application than in the untreated situation, leaving a higher egg density before subsequent applications in treated plots than in the untreated control.

Insecticide Impacts on Natural Enemies. Although Bt sweet corn is a type of genetic resistance, it is treated here as an alternative insecticide because it is planted to replace chemical insecticides. The toxicity of insecticides to the primary predator species in both immature and adult stages was determined in four field trials (Musser and Shelton 2003a). Table 2 lists the average percentage of predators found in the sprayed plots compared with the untreated plots from applications of the full rate of the insecticide. When average predator populations over the four trials were higher in treated plots than untreated plots, populations were considered equal. *T. ostriniae* is vulnerable to insecticides in the adult stage but more protected while developing inside the eggs (Hassan et al. 1987). Pyrethroids and spinosad are toxic to adult *Trichogramma* spp. (Suh et al. 2000, Brunner et al. 2001), but there is no evidence that *B. thuringiensis* has any impact on *Trichogramma* spp. (Mertz et al. 1995, Takada et al. 2001). Therefore, we reduced the percentage of parasitism in the λ-cyhalothrin and spinosad treatments but not the Bt corn treatment in relation to the parasitism rate when not treated (Table 2).

Insecticide Impacts on *O. nubilalis*. In addition to the variability of insecticides in their toxicity to natural enemies, there are also variable levels of pest control from different management options (Musser and Shelton 2003a). Many field studies report total pest control from insecticides. However, when comparing two products, it is helpful to know what proportion of the total control is directly from the insecticide and how much is due to preserved natural enemies. Direct control should be consistent in most situations, but the biological component may not be applicable to different situations. Teasing apart these two components in field studies is not a trivial matter. Because sweet corn insecticide efficacy trials generally use multiple applications, those treatments that have negative impacts on natural enemies actually provide more chemical control than reflected in total control because a lower percentage of insects die from biological control after the initial application than die in the untreated control. Because efficacy is reported in comparison with untreated controls, direct chemical control was adjusted most for λ-cyhalothrin, which has the largest impact on natural enemies, whereas no adjustment was made for Bt corn that has very little impact on natural enemies (Table 2). Larval and adult *O. nubilalis* mortality are not addressed separately in this model but together provide the total chemical control observed in field trials.

Economic Factors. Crop yield and value are inputs supplied by the user to convert the ear damage percentage to an economic cost. Insecticide costs, the Bt sweet corn seed premium and the foliar insecticide application costs supplied by the user are also incorporated into the decision guide. Insecticide costs are calculated for a single application, whereas the planting of Bt varieties and the release of *T. ostriniae* are one-time expenses intended to provide season-long protection. To compare these different management options, we assumed that this guide would be used three times between tassel emergence and harvest resulting in three potential insecticide applications. Therefore, we compare one-third of the total costs of the Bt technology fee and *T. ostriniae* to a single insecticide application.

Economic loss from *O. nubilalis* damage is based on crop value and the percentage of ears that become unusable as a result of *O. nubilalis* feeding. In processing sweet corn, 60% of *O. nubilalis* ear feeding will be in the ear tip where it can be removed during processing (Shelton 1986), causing no economic loss. For both fresh market and processing sweet corn, the value of sweet corn is assumed to be constant regardless of the management options selected (no premium for organic or IPM-labeled produce). Potential costs affiliated with damage such as increased harvest time (fresh market) or outright rejection of the crop when damage is too high (processing) are also not included in the economic threshold calculations, but the user can consider these from the percentage of unusable ears estimated for each management option.

Sensitivity Analysis. We conducted two types of sensitivity analysis of this guide using the economic threshold as the measure of sensitivity: one analysis tested the assumptions used in constructing the guide, and the other tested changes in the parameter values chosen by the user. The assumptions tested were 10% changes for crop maturity adjustment (L in *Appendix* A), aphid adjustment (M), eggs per egg mass (N), predation rate capacity (U), search area (V), parasitism (W), toxin efficacy (Y), and the number of cavities per larva (AA). These assumptions were individually changed and the economic thresholds generated were compared with the economic threshold in the decision guide. The guide was considered sensitive to an assumption if the economic threshold changed >5% as a result of a 10% change in a single factor. The second type of sensitivity analysis compares the economic thresholds generated when one of the values entered by the user is changed. For this evaluation, we calculated the economic thresholds for the scenarios presented in Table 3. Based on our monitoring data, all of these situations are likely to be encountered.

This model has not been validated, so it is not presented as a product ready for field use. Rather this guide is presented as an example of an approach to threshold development that integrates biological and chemical control options in a commercial production system.

Results

The calculations for this decision-making guide are readily computed in a spreadsheet but are too numerous for routine manual calculation. Table 3 shows the economic thresholds determined for a number of scenarios covering the range of situations likely to be encountered in sweet corn. The predator densities used are based on sampling data from New York sweet corn fields between late whorl and milk stages (Musser et al. 2004) (Table 1). The major factors influencing the economic threshold are alternative food sources (aphids and pollen), predator density, and the intended market. The highest economic thresholds occur when predators are more effective, that is, when pollen or aphids are unavailable, and when predator populations are higher. Because of the lower economic value of processing sweet corn, the economic thresholds for processing sweet corn are higher than for fresh market sweet corn. Among control strategies, *T. ostriniae* has the lowest economic threshold in all situations due to its low cost and lack of effect on predation. Among the other control strategies, the threshold never varies by >0.6 *O. nubilalis* egg masses per 40 plants within a scenario. Cost and efficacy are both important in determining the economic threshold for fresh market scenarios, so *T. ostriniae,* λ-cyhalothrin (lowest costs), and Bt corn (highest efficacy) have the lowest fresh-market economic thresholds. Control cost is the overriding treatment factor for lower value processing sweet corn, so *T. ostriniae* and λ-cyhalothrin have the lowest economic thresholds in processing sweet corn.

Among the predator populations, coccinellid larvae influence the economic threshold more than adults, because they consume more eggs per day, tend to be present in higher numbers, and are less affected by

Table 3. Selected economic thresholds generated by the single point-in-time model for scenarios commonly encountered in New York

Scenario				Economic threshold (*O. nubilalis* egg masses/40 plants)						
				Compared with no treatment				Compared with *T. ostriniae* alone		
Market[a]	Predators	Aphids	Maturity	*T. ostriniae*	Cyhalothrin	Spinosad	Bt corn	Cyhalothrin + *T. ostriniae*	Spinosad + *T. ostriniae*	Bt corn + *T. ostriniae*
Fresh	High	High	Fresh silk	1.1	1.4	1.4	1.4	1.7	1.8	1.7
Fresh	Avg	High	Fresh silk	0.2	0.4	0.4	0.4	0.5	0.6	0.6
Fresh	Low	High	Fresh silk	0.2	0.2	0.3	0.2	0.3	0.4	0.4
Fresh	Avg	High	Late whorl	0.8	0.9	1.0	0.9	1.1	1.3	1.2
Fresh	Low	High	Late whorl	0.4	0.4	0.5	0.5	0.6	0.7	0.6
Fresh	Avg	Low	Fresh silk	0.6	0.7	0.8	0.7	0.9	1.0	0.9
Fresh	Low	Low	Fresh silk	0.3	0.3	0.4	0.4	0.5	0.5	0.5
Fresh	Low	Low	Late whorl	0.6	0.7	0.8	0.7	0.9	1.0	0.9
Proc.	High	High	Fresh silk	2.4	3.0	3.6	3.3	4.2	5.1	4.6
Proc.	Avg	High	Fresh silk	1.0	1.4	1.8	1.6	2.3	3.1	2.7
Proc.	Low	High	Fresh silk	0.7	1.1	1.5	1.3	1.9	2.7	2.4
Proc.	Avg	High	Late whorl	1.8	2.3	2.8	2.6	3.3	4.2	3.8
Proc.	Low	High	Late whorl	1.1	1.5	1.9	1.7	2.4	3.2	2.8
Proc.	Avg	Low	Fresh silk	1.4	1.9	2.4	2.2	2.9	3.7	3.3
Proc.	Low	Low	Fresh silk	0.9	1.3	1.7	1.5	2.2	3.0	2.6
Proc.	Low	Low	Late whorl	1.5	1.9	2.4	2.2	2.9	3.8	3.3

Treatment prices used are *T. ostriniae* @ \$0.50/1000, λ-cyhalothrin @ \$78/liter, spinosad @ \$158/liter, Bt sweet corn seed @ \$161/ha, and foliar insecticide application @ \$25/ha.

[a] Fresh market values are 29,652 harvested ears/ha @ \$0.167/ear. Processing market values are 16 ton/ha @ \$65/ton.

[b] Composition of predator complex listed in Table 1.

pollen and aphids than the adults (Table 1). However, for *O. insidiosus,* adults influence the economic threshold more than nymphs, because they are present in higher numbers and are less affected by pollen and aphids than the nymphs (Musser and Shelton 2003c, Musser et al. 2004).

From testing the sensitivity of the economic threshold to the assumptions made in this decision guide, we find that fresh market thresholds are generally sensitive to the assumptions that influence predation (predation rate and the influence of aphids and pollen on *O. nubilalis* egg predation). This is because the economic threshold is based on the difference between treating and not treating, and the expected damage if corn is untreated sensitive to predation. Fresh market situations are more sensitive to predation assumptions than processing situations because some of the damage is removed during processing. When predator populations are low, processing sweet corn thresholds are sensitive to the number of cavities made per larva. All other 10% changes in assumptions changed the threshold <5% (data not shown).

Figure 3 reports output from the 3-wk model for percentage of unusable ears, irreplaceable biological control, and net income for several scenarios. Irreplaceable biological control is the increase in control due to biological control agents. This figure demonstrates the sensitivity of the model to single parameter changes as well as demonstrating how the best management decision varies in different scenarios. In the base scenario, *T. ostriniae,* three applications of λ-cyhalothrin and Bt varieties are slightly profitable, whereas all other treatments are more costly than leaving untreated. However, if aphids are more abundant, the same predator population eats fewer *O. nubilalis* eggs, so the net income improves for all treatments. The scenario of changing *O. nubilalis* egg density has the same total number of eggs as the base scenario, but now the eggs are more numerous during the first week. In this scenario all treatments are profitable, with the single application of spinosad the most profitable. When predators are not present, all treatments are profitable with the broad-spectrum λ-cyhalothrin being the most profitable. In the higher value fresh market scenario, Bt sweet corn provides the highest level of control and is therefore the most profitable option.

Discussion

Brown (1997) mathematically showed how the probability of making an incorrect management decision increases with increasing biological control mortality when using a fixed economic threshold. The decision guide presented here demonstrates this concept empirically and provides a solution for this problem. In the sweet corn system we have biological control agents both uncoupled from *O. nubilalis* density (generalist predators) and linked to *O. nubilalis* density (*T. ostriniae*). By using this new decision-making guide, the best treatment option for a particular situation can be chosen in systems that use biological control agents. Whether the primary concern of the user is pest control, cost, net income, or biological control, the information needed is available to make an informed decision.

Current decision guides in sweet corn make adjustments for the intended market and crop maturity (Dively 1996, Mason et al. 1996, Reiners et al. 2004). However, our decision guide suggests that aphid density and predator populations are also important factors, even when using broad-spectrum insecticides. Although the level of control expected varies little with changes in aphid and predator densities, the

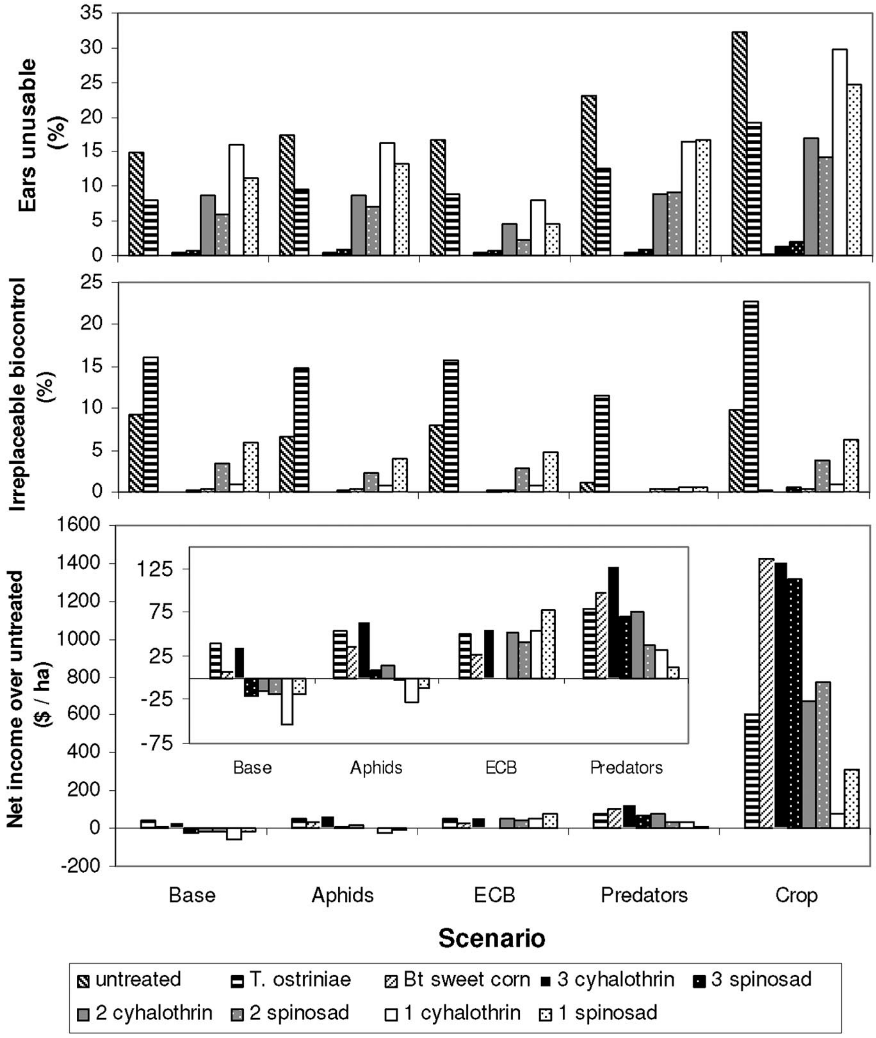

Fig. 3. Three-week decision-making guide results of percent unusable ears at harvest, irreplaceable biological control and net income compared with untreated for applying up to three treatments over 3 wk. Each scenario differs from the base scenario in only one parameter. Base scenario uses a low initial predator density (Table 1), eight per 40 plants with >50 aphids per plant each week, two *O. nubilalis* egg masses per 40 plants each week, processing crop values (16 ton/ha @ $65/ton), and 2002 treatment prices (*T. ostriniae* @ $0.50/1000, λ-cyhalothrin @ $78/liter, spinosad @ $158/liter, Bt sweet corn technology fee @ $161/ha, foliar insecticide application @ $25/ha). Crop maturity is green tassel in week 1, fresh silk in week 2 and brown silk in week 3. The aphid scenario increases aphid density to 15 per 40 plants with >50 aphids each week. The ECB scenario changes the distribution of *O. nubilalis* egg masses to four per 40 plants in week 1 followed by one egg mass per 40 plants in week 2 and 3. The predator scenario is when no predators are present. The crop scenario is when the crop is intended for fresh market and valued at 29,562 ears/ha @ $0.167/ear. Inset in the net income graph shows net income for three scenarios on a smaller scale for clarity. Treatments are no control measures (untreated), a single release of *T. ostriniae* (T. ostriniae), planting a transgenic Bt variety (Bt sweet corn), weekly applications of λ-cyhalothrin or spinosad (three cyhalothrin and three spinosad, respectively), applications of λ-cyhalothrin or spinosad in week 1 and 2 only (two cyhalothrin and two spinosad, respectively), and a single application of λ-cyhalothrin or spinosad in week 1 (one cyhalothrin and one spinosad, respectively).

economic threshold is based on the difference in damage with and without using a control. The damage predicted if untreated is highly variable due to biological control variation, so the economic threshold varies for all the treatment options. Therefore, an understanding of the relationship between pest damage and mortality factors is critical in establishing an economic threshold. Including the choice of management tools in the guide further refines the economic threshold. Because this does not affect the untreated portion of the economic threshold and because more effective tools tend to be more expensive, the economic threshold does not vary as much among treatment options as might be expected when evaluating a

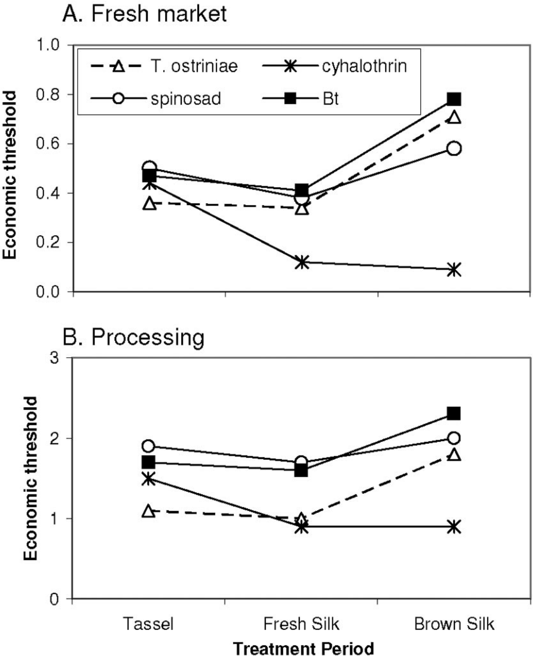

Fig. 4. Economic thresholds for *O. nubilalis* egg masses per 40 plants in sweet corn by using the same treatment in three consecutive treatment windows for the base scenario described in Fig. 3 for (A) fresh market and (B) processing markets.

decision at a single point in time. This does not mean that all treatments are equal over the entire pest control period. Because predator population size is very important in determining the economic threshold, the first use of a treatment that reduces the predator population reduces the economic threshold for future applications (Fig. 4).

Preserving biological control agents has numerous ecological benefits, but a short-term pest management perspective views the benefit of natural enemies merely as the reduction of a pest infestation beyond what would occur from other mortality factors (i.e., irreplaceable biological control). As expected, this irreplaceable biological control is maximized when an additional biological control agent such as *T. ostriniae,* is applied. Bt sweet corn has little impact on natural enemies, but control of *O. nubilalis* is excellent from the Bt toxin, so irreplaceable biological control in Bt sweet corn is minimal. This is also true of weekly applications of spinosad. However, when fewer spinosad applications are made, the benefits of natural enemy preservation are substantial compared with the same number of λ-cyhalothrin applications. Indeed, a single application of λ-cyhalothrin can result in more unusable ears at harvest than if the field had been left untreated due to the negative impact of λ-cyhalothrin on natural enemies. A single application of λ-cyhalothrin also can lead to higher aphid densities (Musser and Shelton 2003a), which further reduces biological control of *O. nubilalis.*

The economic thresholds of the 3-wk model demonstrate the longer term impacts for each management option (Fig. 4). Although the estimated economic thresholds are similar for all treatments during the first week at tassel stage, economic thresholds vary more widely in future weeks. In general, λ-cyhalothrin economic thresholds are reduced due to lower surviving predator populations. As a result, use of products like λ-cyhalothrin move management toward the classic "pesticide treadmill." Use of any of the other options evaluated does not show this trend. These more selective products have approximately the same economic threshold during fresh silk as during the tassel stage, and then a higher economic threshold as the growing predator populations consume more *O. nubilalis* eggs during the brown silk stage.

Another difference between treatments is their stability over changes in the scenario. Because λ-cyhalothrin provides mainly chemical control, the amount of damage expected for a given pest pressure is very stable over biological changes in the scenario (Fig. 3). However, reduced applications of spinosad use both biological and chemical controls, so changes in biological conditions result in more variablility in overall control. Although this may increase the perceived risk when using products such as spinosad, an advantage of using a mix of biological and chemical control methods is that selection pressure by any single tactic is reduced, which could delay the development of resistance to any of these tactics (Gould 1998, Hoy 1998).

The impacts of including biological control factors in the pest management decision-making process are numerous. For a grower, it means that the best treatment option may not always be the same product and that additional factors need to be monitored before making a decision. In this system, monitoring of predators and aphids should not increase the total monitoring time substantially over monitoring for *O. nubilalis* eggs alone, but some increase in monitoring time is expected. Offsetting additional monitoring costs are the opportunities to make fewer insecticide applications and more income. The net economic benefit of using this decision guide will be greatest where biological control is a substantial contributor to overall management.

This guide was designed to demonstrate the potential to improve pest management by incorporating the control provided by natural enemies into the decision-making framework. For processing sweet corn, thresholds from a number of typical scenarios range from 0.7 to 5.1 *O. nubilalis* egg masses per 40 plants with many of the thresholds near the current threshold of two egg masses per 40 plants (Table 3). The fresh market thresholds for these same scenarios are generally <1.0 egg mass per 40 plants, confirming that scouting for eggs is not practical due to the large number of plants that need to be scouted to be confident of being below a small threshold. A moth trap threshold may be more practical in fresh market situations, but because the time between scouting and economic damage is longer when monitoring moths than when monitoring eggs, accurate estimates of pest density and biological control are more difficult to make. The lack of an efficient and accurate sampling method for *O. nubilalis* in fresh market sweet corn is not addressed by this model but is an area that will continue to hamper accurate decision-making.

This guide currently is developed to manage a single lepidopteran pest in sweet corn as frequently occurs in New York. With 19,600 ha of sweet corn grown in New York, and 40% of that for processing (USDA–NASS 2005), this guide can help the decision-makers in this region as presented. However, in many regions and in other cropping systems, multiple pests may attack the crop simultaneously. In sweet corn, *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae) and *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) are additional pests that often require more frequent insecticide applications than *O. nubilalis.* Further research is needed to examine the role of predators and parasitoids in controlling *H. zea* and *S. frugiperda* in sweet corn. An understanding of the interactions of biological control and other management options would facilitate the creation of a decision guide that would assist growers and consultants in managing all three Lepidoptera jointly using a truly IPM approach.

Rather than use a theoretical approach, this guide is based on empirical data and is intended for use with local scouting data during the growing season. The 3-wk model is intended for use in long-range planning and education. It is only during long-range planning where options such as planting Bt sweet corn or making an inoculative release of *T. ostriniae* can be considered. It is hoped that this guide may serve as a tool to stimulate more thought and research so that biological control and selective insecticidal products can be fairly evaluated during the pest management decision-making process.

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Appendix A. Formulae used in single point-in-time model.

Description	Formula
A. *O. nubilalis* egg masses per 100 plants	Actual sampling data per 40 plants * 2.5
B. *C. maculata* adults per 100 plants	Actual sampling data per 40 plants * 2.5
C. *C. maculata* large larvae per 100 plants	Actual sampling data per 40 plants * 2.5
D. *H. axyridis* adults per 100 plants	Actual sampling data per 40 plants * 2.5
E. *H. axyridis* large larvae per 100 plants	Actual sampling data per 40 plants * 2.5
F. *O. insidiosus* adults per 100 plants	Actual sampling data per 40 plants * 2.5
G. *O .insidiosus* nymphs per 100 plants	Actual sampling data per 40 plants * 2.5
H. % plants with >50 aphids	<10, 10–30, >30
I. Crop Maturity	Late whorl, tassel, fresh silk, brown silk
J. Predator count correction	Ratio of absolute and visual sampling methods (see Table 1)
K. Max. egg mass predation per d	Published laboratory data (see Table 1)
L. Crop maturity adjustment	Adjustment for pollen as alternative food (see Table 1)
M. Aphid adjustment	Adjustment for aphids as alternative food (see Table 1)
N. Eggs laid per 100 plants	A * 17 eggs per egg mass
O. *C. maculata* adult predation (eggs/d)	B * J * K * 17 eggs per egg mass * L * M * insecticide survival (see Table 2)
P. *C. maculata* larvae predation (eggs/d)	C * J * K * 17 eggs per egg mass * L * M * insecticide survival (see Table 2)
Q. *H. axyridis* adult predation (eggs/d)	D * J * K * 17 eggs per egg mass * L * M * insecticide survival (see Table 2)
R. *H. axyridis* larvae predation (eggs/d)	E * J * K * 17 eggs per egg mass * L * M * insecticide survival (see Table 2)
S. *O. insidiosus* adult predation (eggs/d)	F * J * K * 17 eggs per egg mass * L * M * insecticide survival (see Table 2)
T. *O. insidiosus* nymph predation (eggs/d)	G * J * K * 17 eggs per egg mass * L * M * insecticide survival (see Table 2)
U. Total potential predation (eggs/d)	O + P + Q + R + S + T
V. Proportion eggs surviving predation	EXP[[−0.2/N]*U] (Nicholson-Bailey model using 0.2 as the search area)
W. Proportion eggs surviving parasitism	if *T. ostriniae* applied, 1− [0.5 * survival (see Table 2)], else 1 − [0.05 * survival]
X. Proportion larvae surviving abiotic factors	0.432 (10% eggs never hatch and 52% larval mortality)
Y. Proportion larvae surviving chemicals	see Table 2
Z. Larvae surviving to infest corn (#/100 plants)	N * V * W * X * Y
AA. Estimated ear cavities (#/100 plants)	0.6 (larvae make 1.5 cavities each with 40% cavities in the ear) * Z
AB. Ears with feeding damage (%)	if [AA / A > 10, (more than 10 cavities per egg mass) then if [A > 20, then 100 (maximum damage is 100%), else A * 5 (5 ears damaged per egg mass)], else if [AA / A >2.5 (between 2.5 and 10 cavities per egg mass), then A * 3.1623 * [AA / A]$^{0.5}$ (fits a curve from 2.5 ears damaged per egg mass at 2.5 cavities per egg mass to 5 ears damaged per egg mass at 10 cavities per egg mass), else AA] (assume 1 ear damaged per ear cavity when less than 2.5 cavities per egg mass)
AC. Harvestable ears unusable (%)	if [processing, then if [AA>250, then 100 (maximum damage is 100%), else if [AA * 0.4 < AB, then AA * 0.4, else AB]], else AB] (lesser of 40% of ear cavities or % ears with damage in processing corn: in fresh market, any damage makes the ear unharvestable)
AD. Control costs ($/ha)	if untreated, then 0, else if Bt or *T. ostriniae*, then 0.3333 * actual cost, else actual cost + application cost (user enters costs)
AE. Damage realized ($/ha)	AC * crop value (user enters crop value as yield * value per unit yield)
AF. Net income over untreated ($/ha)	[AD + AE for untreated] − [AD+ AE for treatment] (threshold is where the net income is 0)

[ ], mathematical parentheses; ( ), explanations.