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$$\frac{dr_1}{dt} = \frac{K}{DEI(t)}\left[r_{in}(t) - r_1(t) \bullet \left(1 + \frac{1}{K} \bullet \frac{d[DEI(t)]}{dt}\right)\right]$$

$$\frac{dr_2}{dt} = \frac{K}{DEI(t)}\left[r_1(t) - r_2(t) \bullet \left(1 + \frac{1}{K} \bullet \frac{d[DEI(t)]}{dt}\right)\right]$$

$$\vdots$$

$$\frac{dr_{out}}{dt} = \frac{K}{DEI(t)}\left[r_{(k-1)}(t) - r_{out}(t) \bullet \left(1 + \frac{1}{K} \bullet \frac{d[DEI(t)]}{dt}\right)\right]$$

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University of Maine

Agrelation: A Computerized Decision-making Tool for Colorado Potato Beetle Population Management and Environmental Quality Concerns

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Contents

Figures

Tables

INTRODUCTION

Many facets of Maine potato production have been simulated with computer models and expert systems (Table 1). Given the ongoing improvement of computer technology and validation of past efforts, scientists can now combine several agricultural submodels into one holistic and user-friendly computer application. This bulletin reports on the development of one such application—*Agrelation*—aimed at modeling a portion of Maine potato production and management.

The motivation and framework for the development of an ecologically based computer model, which could be used to evaluate the ecological and economic dynamics of alternative potato-cropping systems stemmed from a long-term potato ecosystem study initiated at the University of Maine in 1990 (Alford et al. 1996). This multidisciplinary research project had goals of quantifying the ecological interactions between various components found in conventional and alternative potato-production systems. The systems approach was used to develop the research hypotheses and enabled development of several component-level computer simulation models (Drummond and Groden 1996; Long et al. 2000). *Agrelation* builds upon this work in attempting to provide linkages across individual components in the potato ecosystem.

Agrelation integrates three major submodels: (1) the population dynamics of Colorado potato beetle, *Leptinotarsa decemlineata* (Say), the major insect pest of potatoes grown in the eastern United States; (2) Colorado potato beetle pest management strategies and associated tactics; and (3) environmental quality concerns associated with the management of Colorado potato beetle. The integration of these three components can facilitate the design of multiple pest management strategies in light of insect pest damage and environmental quality concerns. In addition, *Agrelation* was designed to be user-friendly and capable of answering a variety of questions, thus targeting a wide range of users and uses (Table 2).

Colorado potato beetle population dynamics and susceptibility to chemical, cultural, and biological controls are specific to the geographic region in which they occur (Tauber et al. 1988; Tauber 1988a, 1988b; Groden 1989; Drummond and Groden 1994). Pesticide interactions with environmental quality are dependent on site-specific information such as soil type and slope of land (Becker et al. 1989). Agricultural environmental cost estimates—such as those derived from willingness to pay survey data—are also dependent on geographic location (Higley and Wintersteen 1992; Ziegler

Table 1. Computer programs and analytical models used for potato production decision making and research investigation.

Focus	Model	Reference	Description
Disease	BLITECAST	Krause et al. 1980	Computerized potato blight (disease) forecasting.
	PDM	Stevenson 1994 (in use 1985)	Potato Disease Management; computer-aided decision support to forecast late and early blight.
Crop management	PCM	Stevenson 1994 (in use 1989)	Potato Crop Management; computer-aided support for potato diseases, insect pests, and irrigation scheduling.
	SPUDGR4	Johnson 1990	Simple potato growth model for crop-pest management (FORTRAN 77).
	SIMPOTATO	Hodges et al. 1992	Modular simulator of crop growth with attention to irrigation and fertilization practices (FORTRAN 77).
	PotatoES	Weisz et al. 1994	Potato expert system aimed at northeastern IPM decision support; focuses on control of insect pests and disease, attention to development of insect pest resistance.
	SIMPOTATO & ARC/INFO	Han et al. 1995	Site-specific crop management tool to study potato yield and N leaching distributions, interfacing between a GIS (ARC/INFO) and SIMPOTATO.
Colorado potato beetle	REPO	Follett et al. 1993	Resistance Evolution in Pest Organisms: Simulation model to predict the rate of resistance development in CPB based on genetic, biological, and management conditions (FORTRAN 77).
	CPBSIM	Drummond and Groden 1994; Long et al. 2000	Time-varying distributed delay used to simulate temperature-dependent insect development as an Erlang density function. Insect stages are broken into boxcars, where number of boxcars represents order of delay and specific instance of Erlang family (LISP).
	PIES	Vencill et al. 1995	Expert system for management of CPB in commercial potato fields on the eastern shore of Virginia.
	CPB simulator	Ferro unpublished	A discrete delay simulation model of CPB. Programmed in Basic as a series of difference equations with delay time based on degree days.
Environmental impact	Water Quality	Becker et al. 1989	Method for determining soil-specific leaching and surface runoff potentials of pesticides.
	EIQ	Kovach et al. 1992	Environmental Impact Quotient; pesticides are ranked based on risk to 11 environmental categories, e.g., parathion EIQ = 104.4, *Bacillus thuringiensis* EIQ = 13.5.
	Environmental Cost Model	Higley and Wintersteen 1992 Ziegler 1999	Assigns environmental cost to an application of pesticide, based on objective criteria regarding risk to 8 environmental categories and subjective willingness-to-pay survey data.

Table 2. Possible uses for *Agrelation.*

Role / Audience	Implementation
Education	Classroom tool for insect population ecology, pest management, pesticide interactions with the environment, and agricultural economics
Research and Development	Modeling tool for Colorado potato beetle population dynamics and development of control strategies; modular design allows for addition of related models
Cooperative Extension	Determining regional potato pest management strategies and assisting producers with fine-tuning pest control strategies
Producers	Timing of pesticide applications, efficient use of pesticides; decision making tool for choosing pest management strategies in light of Colorado potato beetle population and farm-specific environmental concerns; holistic view of agriculture helps producers perceive critical issues in sustainable potato production
Policy makers	Determination of farm-specific pesticide regulation based on allowable levels of environmental risk and/or cost

1999). To make *Agrelation* a flexible program that can be used to simulate a specific geographic locality, model parameters can be determined by the user, and input files representing data collected in a particular location can be easily linked to input needs of the model. These two characteristics are the cornerstones of *Agrelation*.

Agrelation combines computer modeling with environmental economics to create an agricultural decision-making tool. In most economic analyses of agroecosystems, the regional and national tendency is to exclude environmental costs, resulting in a growing schism between conventional and environmentally conscious agriculture (Beus and Dunlap 1990). *Agrelation* attempts to merge these two farming philosophies by assessing environmental risk of pest management strategies.

Indicators of national well-being, such as the Gross Domestic Product, inaccurately portray the health of the country by excluding the importance of social and environmental well-being (Cobb et al. 1993). Current insecticide material costs do not reflect environmental costs associated with the application of these chemicals (Higley and Wintersteen 1997; Ziegler 1999). Maine potato producers do not possess a convenient means to account for the environmental costs and risks of pesticide use. One possible way of accounting for such costs and risks would be to include environmental quality instruction in pesticide training classes, which currently focus on application techniques and personal safety (Dorman 1998). Farmers are uncertain of the risks—generally, yield loss risks—involved upon adopting integrated farming systems (Smith and Marra 1993). *Agrelation* incorporates a more thorough definition of risk—including both environmental and yield loss risks—and can be used to educate users about diversified and alternative pest management strategies.

PROGRAM DESCRIPTION

Agrelation was developed using Microsoft Visual C++®. Graphical user interface (GUI) tools, provided in Microsoft Visual C++®, were used to create the windows interface.

Agrelation was designed to model one growing season per year for a single simulation run. Multiple growing seasons can be simulated by running sequential single season inputs and carrying over the end-of-year model outputs. Maine potato production was divided into six components or modules for modeling purposes. The modules are as follows:

1. Colorado potato beetle population dynamics
2. Control tactics
3. Climate data
4. Natural enemies
5. Cultivar specifications
6. Farm characteristics

Although all six modules have functionality at this point, development of this first version of *Agrelation* has focussed primarily on the first two components.

Windows® Interface

The user interface of *Agrelation* (Figure 1) was designed with three linked and split—but independently active—windows. The "Module Chooser" (Figure 1, top left) was designed as the main tool to navigate through the program. This window remains unchanged as the program is used, while the other two windows display information upon request. From the “Module Chooser,” the user can select any one of the six modules as well as the “Simulation” engine—represented as buttons.

The “Simulation” engine was designed as a staging point for editing simulation-specific information, running simulations, and viewing the results of previously run simulations. Upon selecting the “Simulation” button, the “Simulation Chooser” window (Figure 1, lower left) is updated with previously built and saved parameterized simulations found in the database, discussed later. The user can select any one of the available simulations from the “Simulation Chooser” window. Upon doing so, the window to the right of the “Module Chooser” and “Simulation Chooser” windows displays information pertaining to the chosen simulation in a tabbed format (Figure 1, right side). This information includes simulation start and end dates, the names or instances of the six submodel modules (see above), initial Colorado potato beetle overwintering population, and a note-taking pad. The right side of the screen is where parameter editing of the chosen simulation occurs. The other six submodel modules (see above) adhere to the same split window format, where the user selects an instance of a chosen module from the “Chooser” window on the left and views or edits information specific to that chosen instance in the right window.

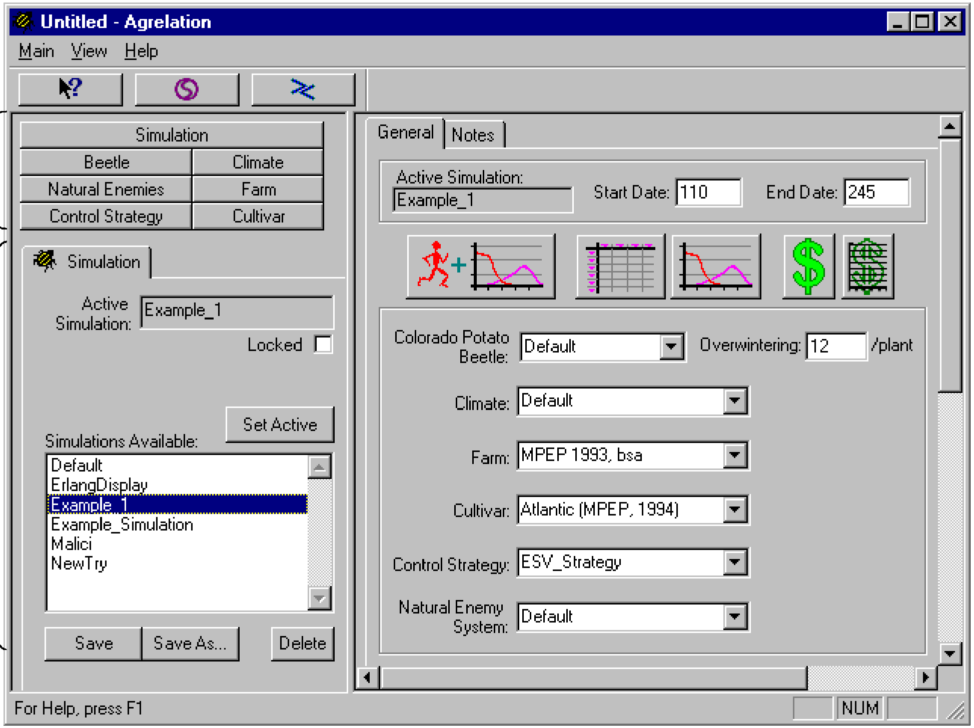
Each of the seven *Agrelation* components (the “Simulation” engine and six modules) contains a note-taking, tabbed window screen (Figure 1, right). Note-taking windows are included for users who wish to document particular simulations and parameters. Notes are specific to any given instance of a module, and each instance of notes can hold up to 64,000 characters (approximately 9,000 words). The notes are saved when specific simulations are saved.

Operating System Requirements

Agrelation requires a minimum of 1.5 Mb of storage space and 16 Mb of RAM, Windows® 95 or 98, and a 486 processor or better. Typical simulation runs require five to 30 seconds using an AMD-K6® chip operating at 266 MHz and 64Mb of RAM. Length of runtime is related to model complexity and is most dependent on the number of days chosen to be modeled and the number of user-activated Colorado potato beetle mortality measures.

“Module Chooser” window, from which the Simulation button has been selected.

“Simulation Chooser” window, from which the simulation entitled, “Example_1” has been set active.



Active Simulation: Example_1

Locked ☐

Simulations Available:

- Default
- ErlangDisplay
- Example_1
- Example_Simulation
- Malici
- NewTry

Active Simulation: Example_1

Start Date: 110

End Date: 245

Colorado Potato Beetle: Default

Overwintering: 12 /plant

Climate: Default

Farm: MPEP 1993, bsa

Cultivar: Atlantic (MPEP, 1994)

Control Strategy: ESV_Strategy

Natural Enemy System: Default

The name of the active Simulation; start and end dates (Julian); run, table, graph, and economic report buttons

Each simulation is defined by six components, declared here along with the initial population density of Colorado potato beetle.

Figure 1. Agrelation main screen, displaying the program framework.

Submodel Modules

1. Colorado potato beetle population dynamics

The population dynamics module conceptualizes population density as the number of Colorado potato beetles on an average potato plant within a field. Parameters and computations specific to Colorado potato beetle population dynamics are categorized as either stage-specific or sub-stage-specific. Colorado potato beetle development and background mortality rates are calculated on a stage-specific basis, as are fecundity and diapause dynamics. Sub-stage-specific relationships are categorized as parameters that are linked to physiological points in an insect's life stage, see consumption and Figure 5.

Life stage-specific development. The Colorado potato beetle life cycle is divided into 12 life stages in *Agrelation*: overwintering adults (in the soil), post-emergent male adults, preoviposition female adults, ovipositing female adults, eggs, first, second, third, and fourth instar larvae, pre-pupae, pupae, and summer adults (Figure 2). The choice of the number of life stages was determined by the ecological processes that we wished to simulate. As an example, each larval instar was modeled so that stage-specific insecticide susceptibility and feeding rates could be incorporated into the model.

A time-varying distributed delay, developed by Manetsch (1976), is used to model Colorado potato beetle development by dividing each of the 12 Colorado potato beetle stages into a number (K) of sub-stages or "boxcars" (Figure 3). This algorithm has been validated and simulates insect phenology quite well (Whitfield et al. 1980). Mathematically, K specifies the member of an Erlang density function (Figure 4), which can be used to simulate the distribution of Colorado potato beetle individual development times (Drummond and Groden 1996); the Erlang distribution is defined as:

$$f(\tau) = [\, (DEL / K)^{K} \bullet \tau^{(K-1)} \bullet e^{(-K \bullet \tau / DEL)} \,] \,/\, (K - 1)! \qquad (1)$$

where t is a random variate representing an individual insect development time and DEL is the mean of the distribution of development times with variance, σ^2:

$$\sigma^{2} = DEL^{2} / K \qquad (2)$$

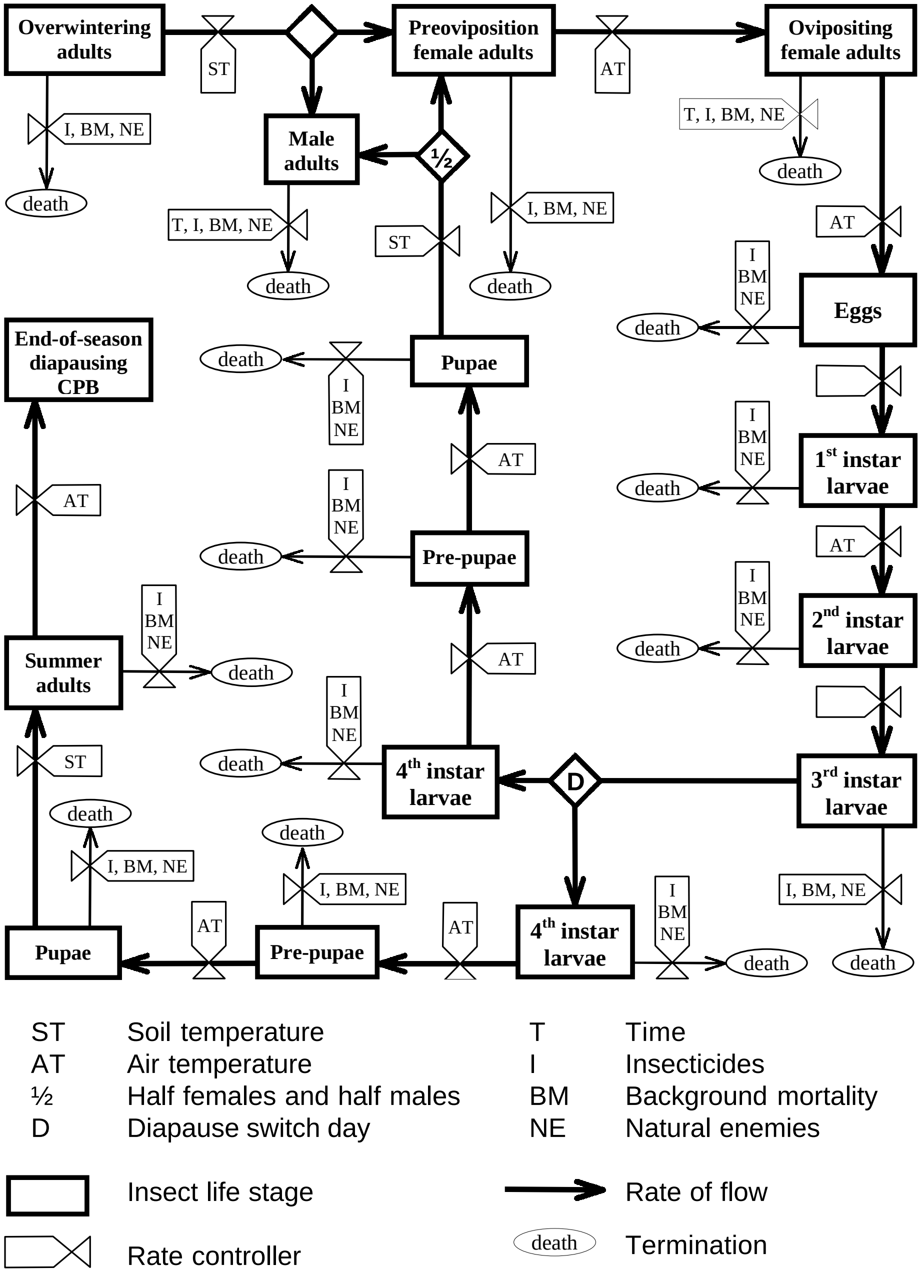
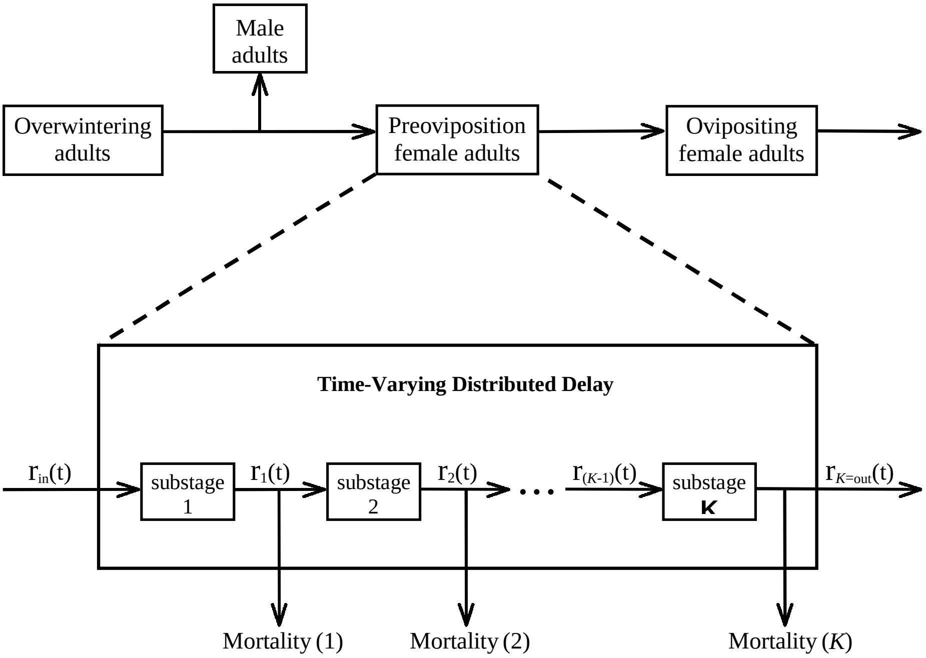


Figure 2. Conceptual representation of Colorado potato beetle population dynamics as modeled in Agrelation.



Differential equations of the delay (Manetsch 1976):

$$\frac{dr_1}{dt} = \frac{K}{DEL(t)}\left[r_{in}(t) - r_1(t)\bullet\left(1+\frac{1}{K}\bullet\frac{d[DEL(t)]}{dt}\right)\right]$$

$$\frac{dr_2}{dt} = \frac{K}{DEL(t)}\left[r_1(t) - r_2(t)\bullet\left(1+\frac{1}{K}\bullet\frac{d[DEL(t)]}{dt}\right)\right]$$

$$\vdots$$

$$\frac{dr_{out}}{dt} = \frac{K}{DEL(t)}\left[r_{(k-1)}(t) - r_{out}(t)\bullet\left(1+\frac{1}{K}\bullet\frac{d[DEL(t)]}{dt}\right)\right]$$

Figure 3. Conceptual model for the time-varying distributed delay.

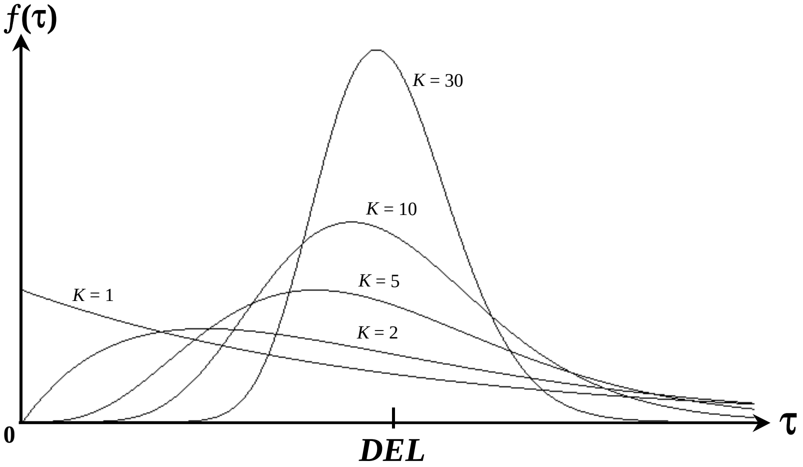


Figure 4. Erlang family of density functions ($f(\tau)$ = *probability density, DEL = arithmetic mean).*

Literature reporting on mean developmental times of insect life stages at varying temperatures such as those of Colorado potato beetle often depicts results in the form of mean number of days for development with a corresponding standard deviation, under the assumption that the data came from a Gaussian distribution. One can estimate a stage-specific K from stage-specific development data for various constant temperatures by assuming the mean and variance based on a normal distribution are similar to a mean and variance described by the Erlang distribution, thereby setting them equal, and solving for K in equation 2 (Drummond et al. 1985; Fan et al. 1991).

Manetsch (1976) shows that when *DEL* varies with time—in our case, Colorado potato beetle development rates depend on temperature, which varies with time—the Erlang distribution can be simulated with a set of K differential equations solved by the Euler integration method. This approximation requires the computer to perform iterative calculations, where K intermediate rates of flow are updated hourly (in real time) for each of the twelve Colorado potato beetle life stages. A time step of one hour was chosen based on algorithm stability, desired computational speed (given a maximum growing season of 365 days), and practical reasons such as temperature data availability and chemical control application at a particular hour in the day. The K intermediate rates of flow yield a storage value (integral of the *K* rates) or, conceptually, a population density of a given Colorado potato beetle life stage on a potato plant.

The relationship between temperature (T, °C) and mean development rate ($1/DEL$, 1/days) for each of the 12 Colorado potato beetle life stages can be determined and parameterized by the user of *Agrelation,* as either linear:

$$1 / DEL = a + b \bullet T \tag{3}$$

where the user can determine constants a (y-intercept) and b (slope), or as a sigmoidal curve:

$$1 / DEL = C \; [\; (1 / [1 + e^{k1 + k2 \bullet T}] \;) - e^{-(Tm - T)/DT} \;] \tag{4}$$

where the user-definable constants C, k_1, k_2, Tm, and DT are functional shape parameters (see Logan et al. 1976, 1985): Default Colorado potato beetle stage-specific development parameters are listed in Table 3.

Potato foliage consumption. Colorado potato beetle foliage consumption is specific to life stage (Logan et al. 1985; Ferro et al. 1985) and physiological age within a life stage (Fargues 1994). *Agrelation* allows the user to determine the amount of leaf area (LA, cm^2) consumed by an individual life stage of Colorado potato beetle for each of the 12 life stages. Because the duration of immature feeding life stages are temperature-dependent, consumption per day is also temperature-dependent (Fan and Drummond 1992). In addition, the distribution of foliage consumption for an individual within a particular life stage can be modeled as constant, normal, or lognormal, where this distribution is divided into *K* increments (Figure 5). Consumption within a life stage modeled as a constant at any physiological age increment, x, is given as:

$$f(x) = LA \, / \, K \, , \text{ for } x = 1 \text{ to } K \tag{5}$$

Consumption within a life stage described by a normal distribution at any increment, x, is given as (Fan and Drummond 1992):

$$f(x) = LA \bullet e^{-.5[(x - \mu)/\sigma]^{\wedge}2} \, / \, [\sigma \bullet \sqrt{(2\pi)}] \, , \text{ for } x = 1 \text{ to } K \tag{6}$$

where μ is the mean:

Table 3. Colorado potato beetle development parameters.

Colorado potato beetle life stage	*Erlang "K"*	------------ Sigmoidal equation constants -------------					
		C	k_1	k_2	Tm	TD	R^2
Egg[a]	39	0.34245	4.0094	-0.18206	35.398	0.73867	0.987
First instar[a, b]	16	0.75743	4.0761	-0.17179	35.701	0.7981	0.956
Second instar[a, b]	18	0.74851	4.0804	-0.18491	34.869	0.8842	0.938
Third instar[a, b]	19	0.61332	4.5224	-0.21014	34.763	0.93385	0.906
Fourth instar[b, c]	15	0.42	4.6	-0.2	35.6	1.6	-
Pre-pupae[b, c]	8	0.47	3.765	-0.134	36.0	1.3	-
Pupae[a, b]	99	0.52574	4.2361	-0.14055	33.862	1.3673	0.957
		---- Linear equation constants ----					
			Y-intercept		Slope		
Overwintering adults[d]	4		0.12171		0.01232		-
Post-emergent males[e]	10		0.04		0		-
Preoviposition females[f]	25		-0.0459		0.0067		0.898
Ovipositing females[e]	10		0.05		0		-
Summer adults[e]	20		0.1		0		-

[a] Data from Logan et al. (1985).

[b] Data from Groden and Casagrande (1986).

[c] Sigmoidal equation constants were fit by eye (with trial and error) to development data, therefore no measurement of fit (R^2) is provided.

[d] Data from Lashomb et al. (1984); linear constants were derived from a mean degree day value, therefore no measurement of fit (R^2) is provided.

[e] Data from Groden and Casagrande (1986); linear constants were derived from single mean development times, therefore no measurement of fit (R^2) is provided.

[f] Data from Drummond et al. (1992).

$$\mu = (K + 1) / 2 \qquad (7)$$

and σ is the standard deviation equal to μ / a, where a is a user-definable constant. Consumption within a life stage can also be modeled by a lognormal distribution at any given physiological age increment, x:

$$f(x) = LA \bullet e^{-.5[(\ln(x) - \mu) / \sigma]^2} / [x \bullet \sigma \bullet \sqrt{(2\pi)}] \text{, for } x = 1 \text{ to } K \qquad (8)$$

where σ is the user-definable shape parameter, and μ is the scale parameter given as:

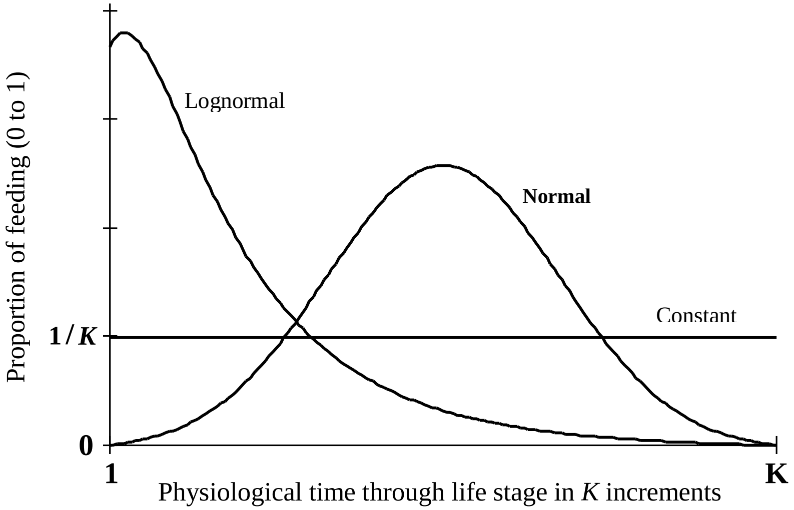


Figure 5. Distribution options for foliage consumption of an individual Colorado potato beetle within a single life stage.

$$\mu = \sigma^2 + \ln(K / a) \qquad (9)$$

where a is a user-definable constant.

Natural mortality. Background mortality of Colorado potato beetle can be modeled for each life stage, where the exact mechanisms of death may or may not be completely understood. Density-dependent mortality has not been explicitly modeled nor included in this version of the simulation. Groden (1989), Cappaert et al. (1991), and Mena-Covarrubias et al. (1996) have documented density-dependent mortality due to predators and parasitoids of Colorado potato beetle in Rhode Island, Mexico, and Michigan, respectively. However, in Maine little evidence exists for density-dependent mortality being a key factor in Colorado potato beetle populations (Drummond and Groden 1996). If the user wishes to simulate mortality due to predation or parasitism, the natural enemy module will allow a static implementation.

Density-independent mortality is calculated as a proportion (P) of the Colorado potato beetle life stage population removed daily—

in terms of Julian days (1 to 365)—and can be defined as a quadratic function of time:

$$\boldsymbol{P = a + b \bullet J + c \bullet J^2} \tag{10}$$

or an exponential function of time:

$$\boldsymbol{P = a + b \bullet J^c} \tag{11}$$

where J is Julian day and constants a, b, and c are user-definable parameters. Linear or constant background mortality can be achieved by selecting the quadratic distribution and setting c or c and b equal to zero, respectively (Fan and Drummond 1992).

Oviposition. Colorado potato beetle fecundity, the number of eggs laid by an average female adult, is a user-definable parameter. The default value is 175.0 eggs per female over her reproductive life span (Drummond et al. 1992). The distribution of egg laying allocation through the female reproductive life-span is simulated by linear decline, which approximates the typical insect fecundity curve described by the Pearson Type I relationship (Carey 1993) and resembles Colorado potato beetle egg-laying (Drummond et al. 1992).

Diapause induction. As Colorado potato beetles pass from third to fourth instar larvae, some fourth instar larvae will continue to develop into pupae and then adults, which will become reproductively active within the same growing season, while other fourth instar larvae will develop into pupae and then diapause-induced adults (the overwintering stage) (see Figure 2). For simulation purposes, this moment during the season—depending on several factors including length of day and geography (Tauber et al. 1988; Tauber 1988a, 1988b; Voss et al. 1988)—can be set to a specific day, which will be referred to as a “diapause switch day.” Larvae maturing to the early fourth stadium before the “diapause switch day” will produce reproductively active adult beetles; those larvae that reach the early fourth stadium after the “diapause switch day” will eventually metamorphose into diapause-induced adults. This day, a user-definable parameter, creates the need for three additional life stages, in addition to the original twelve; specifically, *early* fourth instar larval, *early* pre-pupa, and *early* pupa stages are used to store information specific to those Colorado potato beetle adults that become *late* summer reproductives (non-diapausing adults).

2. Control tactics

The control strategy module consists of user-definable parameters representing information specific to a single pest management tactic—including environmental quality and economic information specific to the application of that control. Multiple control tactics can be used in a single simulation, and the application of each control tactic can be determined by a unique strategy (e.g., different timings or economic thresholds).

Colorado potato beetle control. Once applied, any given control starts with an arthropod effective presence *(AEP)* equivalent to 100%. This presence—not to be confused with soil or field persistence—is used to determine the proportion of insecticide present and capable of killing Colorado potato beetle and natural enemies at any given time after application. The presence remains at 100% until a predetermined point in time (time before decay, *TBD*) is reached, when exponential decay begins (Whitfield et al. 1980), for any given day *x*, according to:

$$AEP(x) = e^{-[\,(\ln(2)) \cdot (x - TBD) / HL\,]} \qquad (12)$$

where *HL* is the arthropod effective half-life of the control (Figure 6). *TBD* and *HL* are both control-tactic-specific and user-definable parameters.

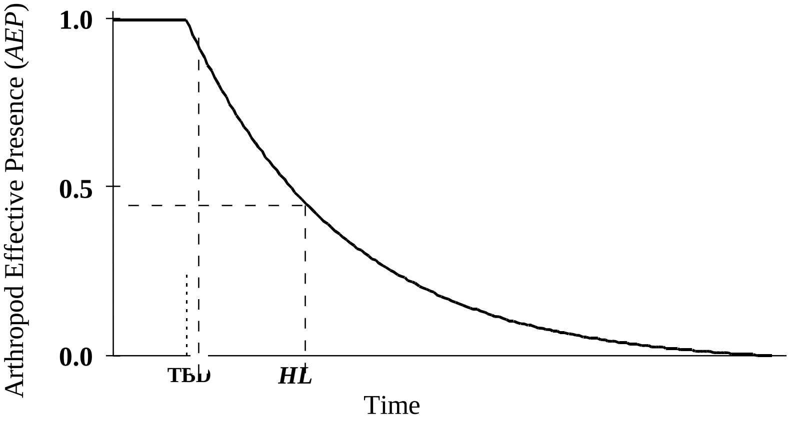


Figure 6. Decay of arthropod effective presence of an insecticide (A = time of application; TBD = time before decay; HL = half-life [of exponential decay]).

Insecticides usually have different efficacies on each of the 12 Colorado potato beetle life stages, and so efficacy is user-definable on a stage-specific and control-tactic-specific basis. Additionally, insecticides may inflict mortality on natural enemies in potato fields. The efficacy of controls on various natural enemies is also user-definable and is designed to be control tactic-specific and natural enemy-specific.

Agrelation is set up to execute all control-induced mortality during the seventh hour of the day; Maine potato producers should apply insecticides at about this hour of the morning, when the sun has risen and drift due to wind is minimal (Spray Drift Task Force 1997). All mortality rates (or efficacies) are multiplied by the proportion of *AEP* before mortality losses are subtracted from the time-varying distributed delays. Colorado potato beetles in a given life stage are removed according to the appropriate efficacy by multiplying the proportion of *AEP* evenly across the *K* intermediate rates of the given stage (Whitfield et al. 1980).

Implementation of control tactics. Control applications through a growing season can be predetermined (that is, calendar based) and/or triggered during the season by set economic thresholds (that is, pest management scout based). The user can also determine a “grace period” for each control tactic—that is, the number of days that must pass between any two applications of the same control. For a calendar-based spray schedule, the user can enter the predetermined days for which a particular control or set of controls are to be applied. The user may also enter economic threshold levels for Colorado potato beetle densities of small larvae (first and second instars), large larvae (third and fourth instars), and feeding adults.

When the seventh hour of any given day occurs, the application schedule is checked. If any one of the thresholds has been exceeded or if the current day is a predetermined application day, and the grace period has been satisfied, then the control is applied. The *AEP* is then used to extract control-induced mortality from each of the Colorado potato beetle life stage time-varying distributed delays.

Environmental quality. Environmental concerns associated with insecticides used on Maine potato farms are incorporated into the economic analysis and pesticide database components of *Agrelation*. The environmental cost model created by Higley and Wintersteen (1992) is used to characterize the interaction between the environment and insecticides. Higley and Wintersteen (1992) surveyed field crop producers in the north central United States requesting participants to rank the importance of various environmental categories, including water quality, human health, and the health of other animals. Participants were also asked for their willingness to pay to reduce or avoid risk to the environment due to insecticides. To apply this model to the Maine potato industry, a similar survey was administered to Maine potato producers of Aroostook County in January 1998 (Ziegler 1999). Environmental category scaling and willingness-to-pay data obtained from the Maine survey have been incorporated into *Agrelation*. The user can edit these parameters so that *Agrelation* can be fine-tuned to a particular potato-growing region and sensitivity analyses can be performed.

The economic component of *Agrelation* requires that environmental risk be set to high, moderate, low, or none for the following eight environmental categories: groundwater, surface water, fish, birds, beneficial insects, chronic human health, acute human health, and toxic risk to other mammals. Insecticide properties and descriptions used to assign risk levels to the environmental categories for *Agrelation* were determined using two pesticide property databases: Hornsby et al. (1996) and EXTOXNET (1998). Higley (1996) has assigned risk levels to various insecticides based on formulated product; this information was also used. A method for determining risk to water quality due to insecticides has been described by Becker et al. (1989) and Goss and Wauchope (1990) and was incorporated into *Agrelation* (Ziegler 1999). The method requires soil and insecticide leaching and surface loss ratings. These ratings are then inserted into the United States Department of Agriculture Soil Conservation Service (USDA SCS) Pesticide Leaching and Run-off Matrices (Figure 7) to obtain leaching and surface loss potentials for the combination of a particular insecticide with a particular soil type. The Pesticide Leaching and Runoff Matrices are incorporated into *Agrelation*. The potential for insecticide leaching—be it high, moderate, or low—corresponds to the level of groundwater risk; similarly, surface loss potential corresponds to surface water risk. Additionally, if a high risk is assigned to surface water, then the risk to fish is moved up one level (from low to moderate, or from moderate to high) unless the risk to fish is already at the highest possible level or there is no risk to fish, in which case no adjustment is made because any degree of surface water contamination will theoretically not affect the fish in this case.

Many soils and insecticides have been assigned leaching and surface loss potentials by the USDA SCS; however, in the absence

Pesticide Runoff Matrix

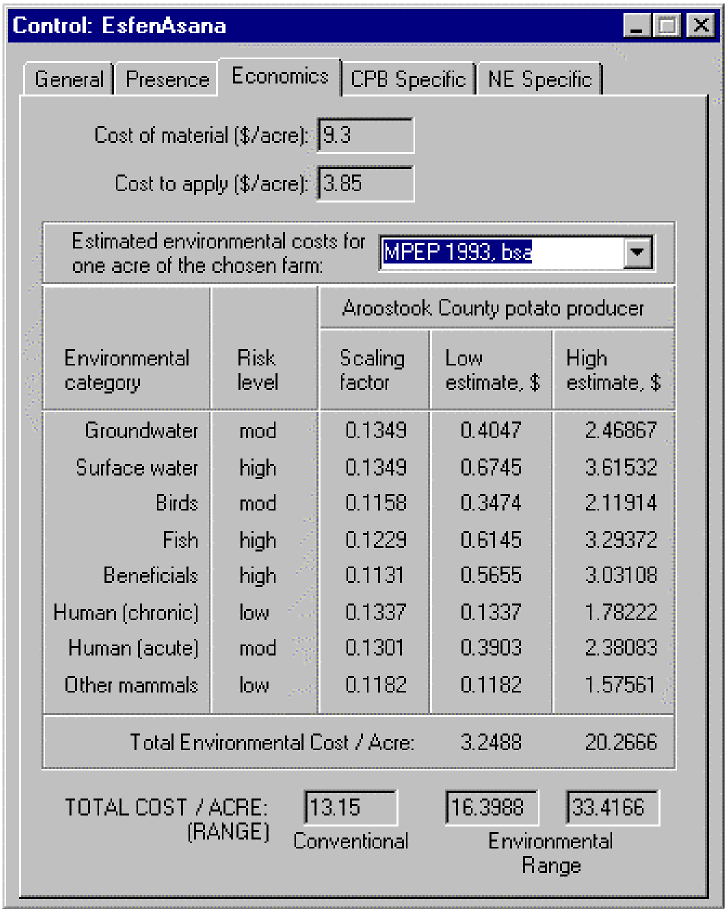
Soil Surface Loss Rating	------ Pesticide Surface Loss Ratings ------ Large	Medium	Small
High	High	High	Moderate
Intermediate	High	Moderate	Low
Nominal	Moderate	Low	Low

Figure 7. USDA Soil Conservation Service Pesticide Leaching and Surface Runoff Matrices (from Becker et al. 1989).

of these designations, the same methodology used by the USDA SCS to assign these ratings can be used to estimate ratings. This methodology uses a series of "if... then..." algorithms assessing soil properties—including surface horizon thickness, organic matter content, surface texture, subsurface texture, and hydrologic soil grouping—and insecticide properties—including water solubility, half life, and soil sorption (Goss and Wauchope 1990). These algorithms are not built into *Agrelation*; however, the three aforementioned insecticide properties are included in the insecticide database for the benefit of users who may be familiar with these properties and related environmental implications. These properties can often be found in pesticide property databases (see Hornsby et al. 1996; EXTOXNET 1998).

Economic analysis. Economic analysis in *Agrelation* resembles that of the University of Maine Potato Ecosystem Project (Marra 1996; Gallandt et al. 1998). Return-over-variable cost (tuber return value minus the sum of variable production costs) is used to measure economic performance. Tuber return value is calculated as the product of yield (cwt) and potato market value ($/cwt). Variable costs include seed, fertilizer, field operation, and insecticide costs, but exclude annualized ownership costs (e.g., mortgage payments and property taxes), which accrue regardless of whether a crop is produced in any given year, and all marketing costs. Potato market value and seed cost are user-definable parameters within the cultivar module. Fertilizer and field operation costs are user-definable parameters within the farm module. Field operation costs include herbicide and fungicide material and application costs as well as manure spreading, disk, cultivation, sidedress, harrow, plant, rolling, roto-beat, and harvest costs.

Insecticide costs include material, application, and environmental costs (Figure 8). Material and application costs, constituting conventional insecticide cost, are user-definable parameters within the control strategy module. Environmental costs are calculated as high and low range estimates based on risk levels for the eight environmental categories, as well as, scaling factors and willingness-to-pay values from the Aroostook County potato-producer survey (Ziegler 1999). Willingness-to-pay values are assigned to insecticide-specific risk levels for each environmental category and multiplied by the corresponding scaling factor. These



Cost of material ($/acre): 9.3

Cost to apply ($/acre): 3.85

Estimated environmental costs for one acre of the chosen farm: MPEP 1993, bsa

Environmental category	Risk level	Aroostook County potato producer		
		Scaling factor	Low estimate, $	High estimate, $
Groundwater	mod	0.1349	0.4047	2.46867
Surface water	high	0.1349	0.6745	3.61532
Birds	mod	0.1158	0.3474	2.11914
Fish	high	0.1229	0.6145	3.29372
Beneficials	high	0.1131	0.5655	3.03108
Human (chronic)	low	0.1337	0.1337	1.78222
Human (acute)	mod	0.1301	0.3903	2.38083
Other mammals	low	0.1182	0.1182	1.57561
Total Environmental Cost / Acre:			3.2488	20.2666

TOTAL COST / ACRE: (RANGE)

Conventional: 13.15

Environmental Range: 16.3988 33.4166

Figure 8. Agrelation insecticide economics window displaying esfenvalerate information.

products are then summed to yield environmental cost estimates. Insecticide costs are calculated for three economic vantage points: conventional, low range environmental, and high range environmental. These insecticide costs—combined with the other variable costs and tuber return value—are used to calculate return-over-variable costs.

3. Climate data

Hourly air and soil temperatures are used within *Agrelation* to assist in determining Colorado potato beetle life stage development rates and potato plant growth rate. Data from weather stations in northern Maine are often recorded in the form of daily maximum and minimum temperatures for soil and air. This data can be extracted from a tab-delimited text file or set to constant values throughout the season within *Agrelation*. Since *Agrelation* runs on an hourly time step, estimates of hourly temperatures are needed. A sinusoidal curve is fit through each daily maximum and minimum temperature. The method used by *Agrelation* has been described by Lando and Lando (1977) for temperature throughout the year, given a high temperature in the summer and a low temperature in the winter. This method has been modified for daily temperature in order to approximate temperature at any given time in the day (Whitfield et al. 1980). The low temperature is assumed to occur at 5:00 A.M., and the high at 2:00 P.M. (EST). A generic sine curve provides the hourly temperature (T) at any given time of day (x):

$$T(x) = A \sin[\,(2\pi / B)\,(x - C)\,] + D \qquad (13)$$

where A is the amplitude (the difference between the maximum and minimum daily temperatures, divided by two), B is the period (24 hours), C is the horizontal shift (the sine wave is shifted dependent on whether the temperature is rising or falling), and D is the degree of vertical shift (the average of the maximum and minimum daily temperatures).

4. Natural enemies

The natural enemy module resembles the control strategy module in that both consist of user-definable components. Each natural enemy component is comprised of information specific to a single natural enemy—including population density and its effect on Colorado potato beetle life stages. This allows multiple natural enemies to be used in a single simulation, and the details pertaining to each natural enemy can be uniquely defined.

Natural enemy population density through time is input as a list of days and the population density corresponding to each day. For intermediate days where density is not provided, natural enemy population density is estimated by linear interpolation from adjacent days and corresponding population densities.

The daily number of a given Colorado potato beetle life stage killed by a natural enemy is entered as a maximum. In other words, if first instar Colorado potato beetle larvae are the only larval prey (i.e., no other Colorado potato beetle larval life stages or any other food sources are present), then the number of first instar larvae that a particular natural enemy can consume in one day is used, as is the case for the ladybeetle, *Coleomegilla maculata* (Groden et al. 1990). This daily unit of consumption is user-definable for all twelve Colorado potato beetle life stages for each natural enemy.

Before natural enemy-induced mortality is accounted for in a simulation, the density of each Colorado potato beetle life stage is calculated as a proportion of total Colorado potato beetle density. Each life stage proportion is then multiplied by its corresponding unit of daily consumption—specific to each active natural enemy. Each of these products equals the stage-specific and natural enemy-specific mortality, which is then subtracted from each corresponding Colorado potato beetle life stage. *Agrelation* conceptually assumes that adults, larvae, pupae, and egg masses will be found and consumed by natural enemies based on the proportion of those Colorado potato beetle life stages that are present and preyed upon by the chosen natural enemies. However, natural enemy preference for given life stages can be simulated by adjusting predation rates (or units of daily consumption). Natural enemy induced mortality occurs on the seventh hour of each day, evenly across the K intermediate rates of any affected Colorado potato beetle life stage. Natural enemies are also affected by insecticides if the user desires.

5. Cultivar specifications

Potato plant growth through the season is modeled as a cumulative leaf area growth process dependent upon air temperature in a similar manner to the development of a single Colorado potato beetle life stage, in accordance with equations 1 through 4. The number of K intermediate rates is user-definable, and the relationship between development rate and temperature can be defined as either linear or sigmoidal. The maximum possible cumulative leaf area (cm^2), accrued in the absence of Colorado potato beetle, is also a user-definable parameter.

We chose to calculate tuber yield (cwt), Y, as a function of seasonal integrated leaf area:

$$Y = AA \bullet MPY / [MA \bullet (1 - PAD)] \qquad (14)$$

where AA and MA are the actual and maximum possible, respectively, potato plant leaf areas integrated over the simulated growing season, MPY is the user-definable maximum possible yield, and PAD is the user-definable proportion of allowable defoliation before significant yield loss occurs (Figure 9). We developed this method based on the work of Milthorpe and Moorby (1974), which lends more support to using *total* seasonal leaf area rather than *peak* or *end-of-season* leaf areas when determining final yield. Also, in accord with work cited by Tamaki (1981), this method for calculating yield intrinsically assigns more weight to defoliation that occurs during potato plant bloom and less weight to defoliation that occurs at the beginning and end of the potato plant physiological life span. Additionally, some defoliation of potato plants might not affect yield (Mena-Covarrubias et al. 1996), so a proportion of allowable defoliation (PAD) has been incorporated into the yield calculation to take into account negligible defoliation.

6. Farm characteristics

The farm module information is required for the environmental quality component of *Agrelation*. Specifically, this is where the user enters the farm soil types. Each farm field is allowed up to five

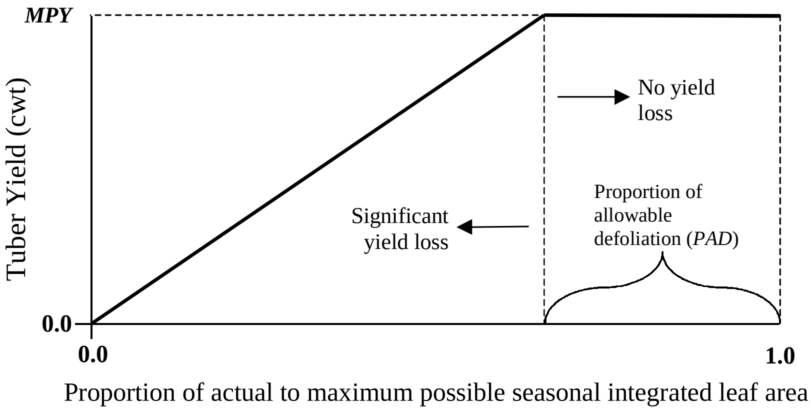


Figure 9. Tuber yield as a function of seasonal integrated leaf area (MPY = maximum possible yield).

different soil types constituting five individual percentages of the field (summing to 100% of the field) and at five individual average percent slopes (i.e., the grade of the land). Each soil type is linked to its respective leaching and runoff potential rating (see Environmental Quality section). If any soil type exists at an average slope greater than 15%, a red flag condition described by Goss and Wauchope (1990), then the runoff potential is increased to the next level of risk, unless it is already at the highest level of risk. Scaled average values for leaching and runoff potential are based upon soil percentage representation on the farm. These final two averages are used to determine risk to groundwater and surface water, as described earlier in the Environmental Quality section.

Data Storage

Input parameterization

A database template was created using Microsoft Access® to store the parameters in *Agrelation*. Parameters can be edited using the *Agrelation* windows interface or by using database software such as Microsoft Access®. *Agrelation* database management was designed using Data Access Objects (DAO)® code included with Microsoft Visual C++®. *Agrelation* makes use of data storage technology developed by Microsoft®, while remaining independent of a particular database management system.

Agrelation parameters are stored in database tables by topic (Figure 10). The *Agrelation* windows interface closely mimics data storage organization and vice versa; an interface window was created for each major data storage topic or each box as shown in Figure 10. There are, however, more windows than database tables; the additional windows are needed to reduce screen clutter with a hierarchical classification of parameters.

Hierarchical relationships between tables have been established within *Agrelation* (see Figure 10), as opposed to using the relationship tools included with Microsoft Access®. Each record of the “Simulation” table stores the data constituting one unique simulation. As an example, each “Simulation” record holds the name or instance of a farm—referencing a single record of the “Farm” table with that name. The “Farm” table stores information pertaining to the physical characteristics of a farm, such as soil composition. Each “Farm” record holds the names of those soils present on a particular farm. Each record of the “Soils” table represents site-specific information pertaining to a single soil, such as the propensity for a soil to allow a pesticide to leach into groundwater. Tiers of complexity allow a novice user to navigate to

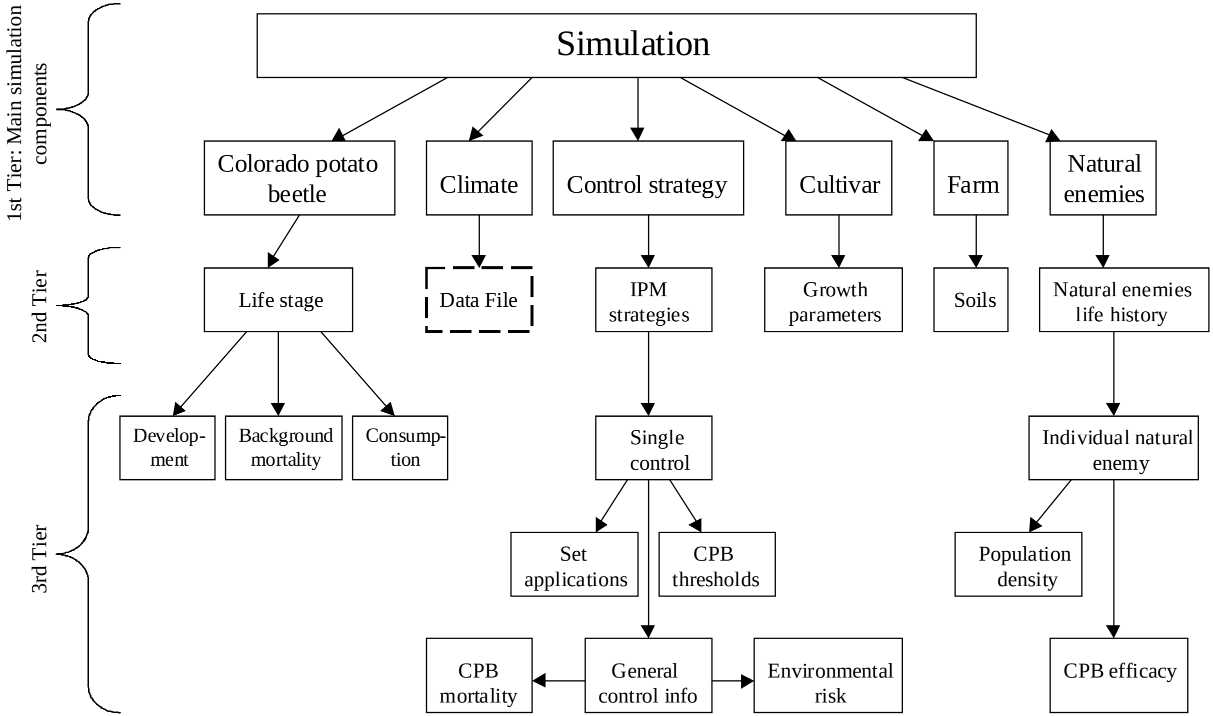


Figure 10. Agrelation data storage organization. (Each box represents a table within the Agrelation database file except for the climate "Data file" dashed box, which represents a tab-delimited text file.)

the “Climate” module and choose a year with warm summer temperatures compared to a year with cool summer temperatures. A more advanced user might alter temperature-dependent relationships associated with Colorado potato beetle larval development at a deeper level. This hierarchical design prevails throughout the program.

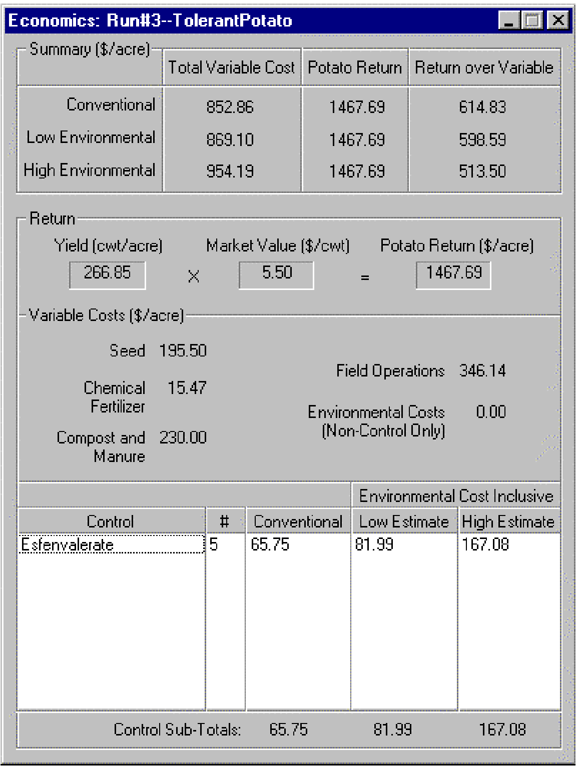
One advantage of the database-supported design is that during development and construction of the *Agrelation* interface, simulation code could be debugged, augmented, and validated by avoiding the interface and using Microsoft Access® to parameterize simulations. Additionally, not all parameters are alterable from the *Agrelation* interface. For example, control-specific environmental risk parameters cannot be altered using the interface but can be edited using Microsoft Access®. If pesticide regulation is ever guided using a program like *Agrelation*, then it might be inappropriate for some users to have immediate editing access of toxicity information specific to insecticides.

Output of results

Economic report. Throughout the six modules of *Agrelation*, economic parameters are tracked, generally in the form of variable costs per acre. The following user-definable variable costs can be found in their respective modules: control material, control application, farm operations, farm fertilizer, farm environmental costs other than those accrued from attempting to control Colorado potato beetle, and cultivar seed. In addition, potato yield is converted to dollars with a user-definable cultivar selling price ($/cwt).

Agrelation output is saved as two text files for each unique simulation. One text file contains a summary of economic report information, and the other contains the Colorado potato beetle population dynamics output (discussed later). The economic report contains three summaries: conventional estimates excluding environmental costs; low-range estimates including a low-range environmental cost; and high-range estimates including a high-range environmental cost. Variable costs and return-over-variable costs are calculated and reported for each of the three economic scenarios. Users can display the economic report as a non-interactive window (Figure 11) or as text in a word processor.

Colorado potato beetle population dynamics report. The second output file, a tab-delimited text file, contains the simulated field data specific to a simulation. Daily calculated values are stored for



Summary ($/acre)

	Total Variable Cost	Potato Return	Return over Variable
Conventional	852.86	1467.69	614.83
Low Environmental	869.10	1467.69	598.59
High Environmental	954.19	1467.69	513.50

Return

Yield (cwt/acre) 266.85 × Market Value ($/cwt) 5.50 = Potato Return ($/acre) 1467.69

Variable Costs ($/acre)

Seed 195.50

Chemical Fertilizer 15.47

Compost and Manure 230.00

Field Operations 346.14

Environmental Costs (Non-Control Only) 0.00

			Environmental Cost Inclusive	
Control	#	Conventional	Low Estimate	High Estimate
Esfenvalerate	5	65.75	81.99	167.08
Control Sub-Totals:		65.75	81.99	167.08

Summary from three economic vantage points: conventional estimates exclude environmental costs; low environmental estimates include a low-range environmental cost; and high environmental estimates include a high-range environmental cost.

Variable cost break-down for pesticides (of which there is one) used in this simulation from the three economic vantage points. Conventional costs include material and application costs only. Environmental costs sum conventional costs and environmental cost range values—both low and high—respectively.

Figure 11. Economic output, display window only (non-interactive).

population densities of each Colorado potato beetle life stage, potato plant leaf area present and consumed, and average temperatures. The graphing application included with *Agrelation* can be started from the "Simulation" module (Figure 1) in order to view these data as a function of time.

Help

Agrelation supports context-sensitive Windows® help throughout all the windows and tabbed windows within the main screen. The Microsoft Foundation Class (MFC) Library, included with Visual C++®, was used to design the help framework. The user can enter the help mode by selecting the toolbar item illustrated with an arrow and question mark at the top right corner of the *Agrelation* main screen (Figure 1). Upon selecting this toolbar button, the mouse-controlled cursor can be moved over a particular area of the program and clicked again, in order to view a description about that area and, in some cases, links relating to other modules in the program.

EXAMPLE SIMULATIONS

Parameterization

Several simulations have been parameterized, run, and analyzed. The objective of these example simulations is to demonstrate the scope of results that can be produced with *Agrelation,* as well as, some basic conclusions about control of Colorado potato beetle on Maine potato farms. Specifically, three insecticides—differing with respect to insect pest efficacy, "environmental friendliness," and cost—have been chosen to control Colorado potato beetle for these examples. The parameterization of the simulations varies according to initial Colorado potato beetle overwintering density, control strategy, and potato plant sensitivity to defoliation. Whenever possible, input parameters were set based on information specific to Maine and other northeastern states for the chosen year of 1993. Weather data from the University of Maine Aroostook Potato Research Farm in Presque Isle, Maine, was used as climate input.

Colorado potato beetle development and consumption parameters for the simulations are listed with source citations in Tables 3 and 4. The diapause switch day was 25 July (Voss et al. 1988). Fecundity was 175.0 eggs per female (Drummond et al. 1992). Background mortality of Colorado potato beetle was zero for all life stages. In addition, no Colorado potato beetle natural enemies were selected to be active. The initial overwintering Colorado potato beetle density was 2.0 per plant.

The potato cultivar Atlantic was chosen for the simulations. Germination occurs approximately two weeks after planting, which for these simulations was 28 May (Porter 1996). Atlantic leaf area accumulation occurs over a period of approximately 70 days, and development parameters were set accordingly; the Erlang K parameter for the potato growth distributed delay was 10, and the relationship between temperature and leaf area increase was described by equation 3, with $slope$ = 0.0 [1/(day•°C)] and y-

Table 4. Colorado potato beetle consumption.

Colorado potato beetle life stage	Leaf area (cm^2)
Post-emergent males[a]	5.0
Preoviposition females[a]	5.0
Ovipositing females[a]	5.0
First instars[b]	1.13
Second instars[b]	1.64
Third instars[b]	4.97
Fourth instars[b]	25.71
Summer adults[a]	10.0

[a] Drummond unpublished data.
[b] Logan et al. (1985)

intercept = 0.024 (1/day). Atlantic vines are generally destroyed by early September, at which time the example simulations were terminated (8 September; Porter 1996), and yield was calculated. Maximum possible leaf area was 3180 cm^2, which was equivocated to a maximum possible yield (*MPY*) of 266.85 cwt per acre (Mena-Covarrubias 1995). A defoliation-tolerant potato plant scenario was simulated with a proportion of allowable defoliation (*PAD*) equal to 15.0% (Mena-Covarrubias 1995). A second defoliation *sensitive* plant scenario was simulated with a *PAD* equal to 0.0% (Mena-Covarrubias 1995).

The following farm and cultivar costs were based on the variable cost information for the 1993 growing season at the Maine Potato Research Farm in Presque Isle, Maine. Specifically, information from the amended soil management, bio-intensive pest management, and Atlantic potato variety study was used (Marra 1996). The following are costs per acre of this study: chemical fertilizer was $15.47; compost and manure were $230.00; field operations were $346.14; and seed was $195.50 (Marra 1996). The potato selling price was $5.50/cwt (Marra 1996).

Soil type-specific information for the state of Maine was obtained from the USDA SCS (1993). Five soils common to the northern Maine potato agroecosystem were chosen at random; their average slopes were below 15%. These five soils, along with approximately 85% of soil types being used to farm potatoes in Maine, have high leaching potential (USDA SCS 1993); therefore, based on the Pesticide Leaching Matrix (Figure 7), risk to groundwater is likely to increase depending on pesticide-specific information.

Esfenvalerate, rotenone, and *Bacillus thuringiensis* (*Bt*) were chosen as Colorado potato beetle control tactics. Efficacy on Colorado potato beetle and environmental risk data for the controls are presented with source citations in Tables 5 and 6. Each control was given an arthropod-effective presence of one day by setting each arthropod-effective half-life to zero. Environmental costs not related to controlling Colorado potato beetle were zero. The grace period between any two applications of the same insecticide was seven days.

Table 5. Efficacy of selected insecticides on Colorado potato beetle.

	Proportion mortality		
Colorado potato beetle life stage	Esfenvalerate[a]	*Bacillus thuringiensis* (Bt)[b]	Rotenone[c]
Adult	0	0	1.00
Egg	0	0	0
First instar	0.966	0.80	0.82
Second instar	0.966	0.80	0.82
Third instar	0.92	0.64	0.82
Fourth instar	0.92	0.64	0.82
Pre-pupa	0.92	0	0
Pupa	0	0	0

[a] Asana® XL 0.66 EC @ 0.02 lb/acre (Stoltz and Matteson 1996).
[b] MTrak® @ 2.5 qts/acre (Sirota et al. 1993).
[c] Rotenone® 0.38E @ 0.25 lbs/acre (Linduska 1986).

Table 6. Environmental risk for selected insecticides.

Environmental category	Esfenvalerate[a]	*Bacillus thuringiensis* (Bt)[a, b]	Rotenone[b]
Suface water	high	none	low
Groundwater	low	low	low
Fish	high	low	high
Birds	moderate	none	low
Beneficial insects	high	none	low
Chronic human health	low	low	low
Acute human health	moderate	none	moderate
Other mammals	low	none	low

[a] EXTOXNET (1998).
[b] Higley (1996).

RESULTS AND CONCLUSIONS

Control strategies and simulation results are presented in Tables 7 and 8. Each of the 22 simulations included two runs—one with the defoliation-tolerant potato plant and the other with the defoliation-sensitive potato plant. When no control strategies were implemented, the chosen parameters resulted in 92.6% defoliation and 64.4 end-of-season diapausing Colorado potato beetles per plant (simulation 2).

The simulation results bring to light four major points: (1) conservative insecticide application threshold levels can lead to environmental costs of $100 per acre; (2) threshold levels of larval and adult densities might not be as effective in planning insecticide applications as other discernable points within Colorado potato beetle seasonal development; (3) accounting for end-of-season diapausing Colorado potato beetle density can affect control strategy success; (4) attempts to control Colorado potato beetle with a combination of insecticides targeting both larval and adult life stages throughout a growing season might be more effective than the use of insecticides targeting larvae or adults only.

The inefficient use of certain insecticides can result in unnecessary high environmental costs. Maine Cooperative Extension population density threshold levels (4.0 small larvae per plant, 1.5 large larvae per plant, 0.5 adults per plant) appear to be lower or more conservative than necessary for effectively controlling Colorado potato beetle. Simulation runs using threshold levels up to five times those of Cooperative Extension levels showed success in controlling Colorado potato beetle defoliation and keeping end-of-season diapausing Colorado potato beetle density below 4.0 per plant (simulations 3-7, 9-11, and 15-19). These results are corroborated by research conducted by Mena-Covarrubias (1995), who found that threshold levels could range as high as 12 to 15 larvae per plant.

Each application of esfenvalerate incurs a high range environmental cost of $20.27 per acre (Figure 8), resulting in return over variable estimates $100 lower than corresponding conventional estimates when five applications of esfenvalerate were used (simulations 3 and 4). However, the number of applications being used is partly dependent on the residual effects of any given insecticide; for these simulations, the insecticides incur a one-time mortality on Colorado potato beetle with no residual effects. While not implemented here, residual effects can be parameterized within the control strategy module (Table 9). In addition, it is important to

Table 7. Simulation runs: insecticide parameterization and Colorado potato beetle population dynamics results.

Run #	App. code[a]	Insecticide[b] (# of applications), Julian days of applications	Total foliage consumption (cm^2)	%of total foliage consumed	End-of-season diapausing CPB/plant
Initial overwintering Colorado potato beetles/plant = 0.0					
1	-	No insecticides applied	0.00	0.00	0.000
Initial overwintering Colorado potato beetles/plant = 2.0 for the remaining simulation runs					
2	-	No insecticides applied	2943.19	92.55	64.355
3	CE*1	Esv (5), 192, 199, 206, 213, 220	159.25	5.01	0.482
4	CE*2	Esv (5), 193, 200, 207, 214, 223	154.49	4.86	0.334
5	CE*3	Esv (4), 196, 203, 210, 217	216.31	6.80	1.303
6	CE*4	Esv (4), 199, 206, 213, 223	204.72	6.44	0.560
7	CE*5	Esv (3), 201, 208, 217	310.28	9.76	1.783
8	egg-2	Esv (2), 199, 216	652.58	20.52	4.245
9	CE*1	*Bt* (6), 192, 199, 206, 213, 220, 227	317.08	9.97	2.757
10	CE*2	*Bt* (5), 193, 200, 207, 214, 221	365.44	11.49	3.832
11	CE*3	*Bt* (5), 196, 203, 210, 217, 224	367.85	11.57	3.098
12	CE*4	*Bt* (4), 199, 206, 213, 220	441.74	13.89	4.354
13	CE*5	*Bt* (3), 201, 208, 216	640.29	20.13	8.677
14	egg-2	*Bt* (2), 199, 216	1191.40	37.47	18.484
15	CE*1	Rot (4), 173, 180, 208, 215	74.77	2.35	1.466
16	CE*2	Rot (4), 176, 203, 210, 217	114.07	3.59	1.451
17	CE*3	Rot (2), 180, 215	198.73	6.25	3.002
18	CE*4	Rot (3), 199, 206, 215	266.51	8.38	2.732
19	CE*5	Rot (3), 201, 208, 216	300.13	9.44	2.716
20	egg-2	Rot (2), 199, 210	411.17	12.93	6.773
21	wint egg-1	Rot (1), 184 *Bt* (1), 215	204.08	6.42	1.069
22	wint egg-1	Rot (1), 184 Esv (1), 215	163.09	5.13	0.501

[a] Application codes are defined as follows: "CE*x" indicates that a multiple "x" of Cooperative Extension threshold values were used in determining when to apply a given insecticide; Cooperative Extension threshold levels are 4 CPB small larvae per plant, 1.5 CPB large larvae per plant, and 0.5 CPB adults per plant; "egg-2" indicates that a given insecticide was applied at peak first-generation egg denisty and again at the end of first-generation egg hatch; "wint" indicates that a given insecticide was applied once at the end of overwintering CPB emergence; "egg-1" indicates that a given insecticide was applied once at the end of first-generation egg hatch.

[b] Esv (esfenvalerate), Asana® XL 0.66 EC @ 0.02 lb/acre; *Bt* (*Bacillus thuringiensis*), MTrak® @ 2.5 qts/acre; and Rot, Rotenone® 0.38E @ 0.25 lbs/acre.

Table 8. Simulation runs: tuber yield and economic results.

	--- Tolerant Potato (PAD[a] = 15.0%) ----				--- Sensitive Potato (PAD[a] = 0.0 %) --			
		Return over variable cost ($/A)[b]				Return over variable cost ($/A)[b]		
Run #	Tuber yield (cwt/A)	Conventional	Low environmental	High environmental	Tuber yield (cwt/A)	Conventional	Low environmental	High environmental
Initial overwintering Colorado potato beetles/plant = 0.0								
1	266.85	680.58	680.58	680.58	266.85	680.58	680.58	680.58
Initial overwintering Colorado potato beetles/plant = 2.0 for the remaining simulation runs								
2	173.39	166.51	166.51	166.51	147.38	23.46	23.46	23.46
3	266.85	614.83	598.59	513.50	259.31	573.35	557.11	472.02
4	266.85	614.83	598.59	513.50	259.07	572.03	555.79	470.70
5	266.85	627.98	614.99	546.92	257.01	573.87	560.87	492.80
6	266.85	627.98	614.99	546.92	256.08	568.72	555.72	487.65
7	266.85	641.13	631.39	580.33	251.64	557.45	547.70	496.65
8	266.85	654.28	647.78	613.75	236.02	484.68	478.18	444.15
9	266.85	495.48	491.51	460.15	251.61	411.67	407.70	376.33
10	266.85	526.33	523.02	496.89	250.42	435.95	432.64	406.50
11	266.85	526.33	523.02	496.89	249.48	430.76	427.45	401.31
12	266.85	557.18	554.54	533.62	246.62	445.87	443.23	422.31
13	266.85	588.03	586.05	570.36	238.85	433.99	432.00	416.32
14	253.51	545.50	544.18	533.72	215.48	336.35	335.03	324.58
15	266.85	526.18	517.00	458.10	263.69	508.78	499.60	440.70
16	266.85	526.18	517.00	458.10	261.22	495.22	486.04	427.13
17	266.85	603.38	598.79	569.34	258.95	559.90	555.31	525.86
18	266.85	564.78	557.90	513.72	252.43	485.46	478.57	434.39
19	266.85	564.78	557.90	513.72	250.39	474.23	467.34	423.17
20	266.85	603.38	598.79	569.34	246.80	493.09	488.50	459.05
21	266.85	611.13	608.18	588.22	258.41	564.70	561.74	541.79
22	266.85	628.83	623.29	591.54	259.34	587.49	581.95	550.20

[a] *PAD* = proportion of allowable defoliation, before significant yield loss, calculated as a proportion of actual to maximum possible seasonal integrated leaf area.

[b] Return over variable costs calculated conventionally exclude environmental costs, while low and high environmental return over variable costs include a high and low range environmental cost estimate, respectively, within variable cost calculation.

Table 9. Residual effects of selected insecticides.

Insecticide	Reported half-life on foliage[a]
Esfenvalerate	3.8 hours
Bacillus thuringiensis	14–28 days
Rotenone	2–3 days

[a] Karmin (1997).

note that our example simulations do not include any natural mortality.

The critical nature of insecticide application timing is emphasized by the simulation results. Considering tuber yield and end-of-season diapausing Colorado potato beetle density, multiple pairs of simulations (3 & 4, 5 & 6, 10 & 11, 15 & 16, 17 & 18, and 18 & 19) indicate that higher threshold levels can alter application timing in such a way as to kill more Colorado potato beetles than accomplished with lower threshold levels (Figure 12). This brings to question current threshold-based application methods. Specifically, basing insecticide applications on larval and adult densities might not be as effective in timing applications as using other seasonal indicators. Egg hatch for the simulations takes place over a period of about 35 days, and larval development takes approximately 17.7 days at an average temperature of 19.4°C (except for simulations including early applications of rotenone: simulations 15-17, 21, and 22). By applying an insecticide that targets larvae at peak egg density and again at the end of egg hatch, almost all larvae are affected. This technique was successful at controlling within-season defoliation, as shown with simulations 8 (Figure 12), 14, and 20; however, the end-of-season diapausing Colorado potato beetle density was more than twice the initial overwintering density for all three simulations, which has implications for the following year's pest management.

Agrelation accounts for end-of-season diapausing Colorado potato beetle density, which can affect the measure of success assigned to a particular control strategy. Some control strategies allow end-of-season Colorado potato beetle density to exceed the initial overwintering density while effectively controlling within-season defoliation (simulations 8-13, 17-20). Control strategies that account solely for control of within-season defoliation, while ignoring end-of-season insect pest density, could have the effect of making insect pest control more difficult the following year.

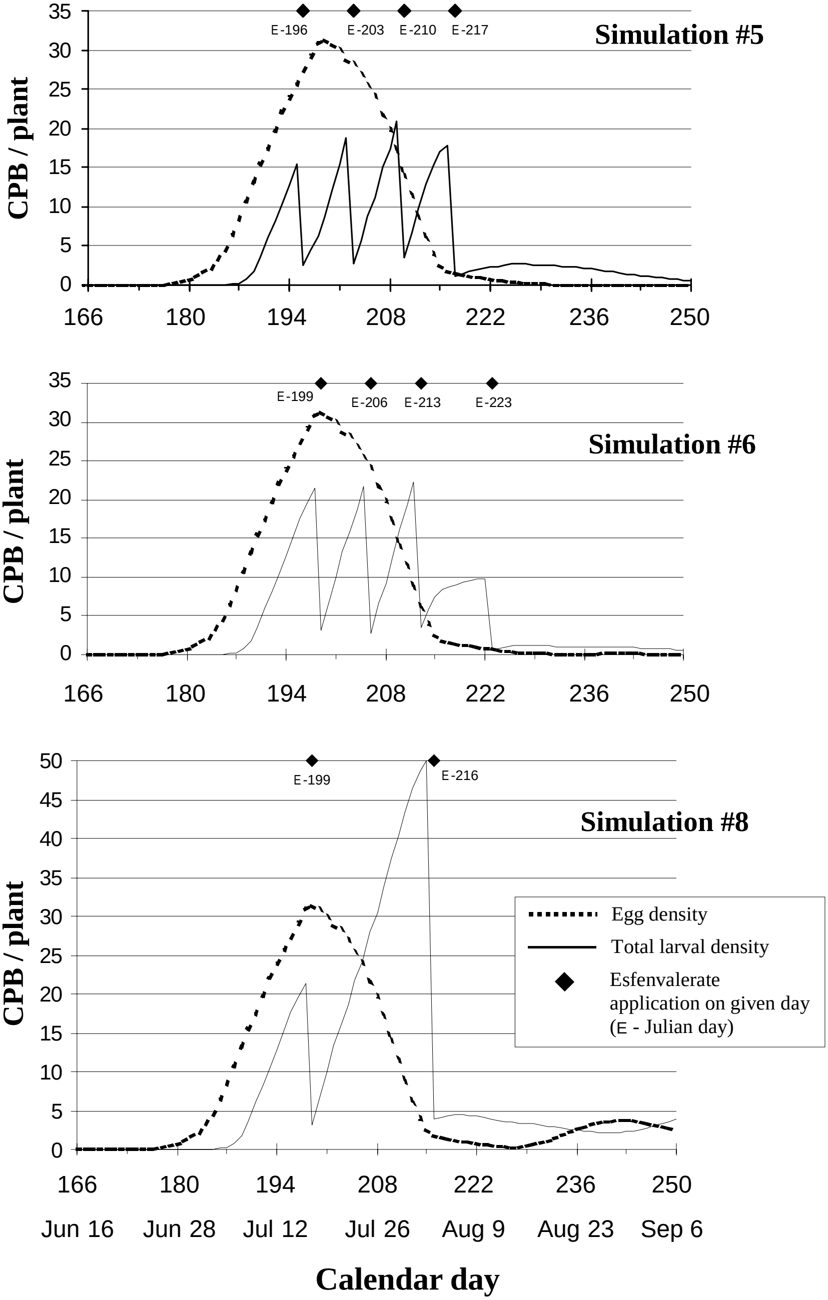


Figure 12. The effect of application timing.

Simulations 17, 21, and 22 show that early season application of rotenone can effectively control post-emergent spring adults, thereby decreasing egg production. Simulations 21 and 22 indicate that rotenone—when applied at the end of emergence (Julian day 184)—decreases Colorado potato beetle density to the point where a single application of an insecticide targeting larvae could be applied at the end of egg hatch, thereby successfully controlling defoliation and end-of-season density of diapausing Colorado potato beetle (see Table 7 and Figure 13). Additionally, the final two simulations (21 and 22) have relatively high return-over-variable costs for all three economic regimes (see Table 8).

Presented here are a few of the possible types of experiments that can be conducted using *Agrelation*. We have not provided extensive analysis of our simulation runs since our intent was more to demonstrate potential applications of the program rather than answer any specific questions regarding pest management strategies for Colorado potato beetle.

EPILOGUE

Future

The modular design of *Agrelation* facilitates future integration of additional components and augmentation of existing components. Improvements might be adaptations of other models listed in Table 1. For example, the current cumulative potato leaf area growth process might be replaced with a more realistic potato development model such as SPUDGR4 (Johnson 1990). In this case, some Colorado potato beetle stage-specific development functions present in *Agrelation* code could be adapted for modeling potato plant stage development.

Contributions to *Agrelation* might extend beyond the original design objectives of modeling Maine potato production. A conceptual tier could be integrated just below the simulation module, aimed at modeling a wider breadth of agricultural pest problems, such as weeds, plant pathogens, and insect pests other than Colorado potato beetle. In turn, the environmental risk and cost components might extend beyond insecticides to include other sources of possible environmental risk such as herbicides, fungicides, and erosion. Also, the cultivar component could be changed to include non-potato crops, for which development data exists. The modular shell of *Agrelation* could be made to model several agroecosystems.

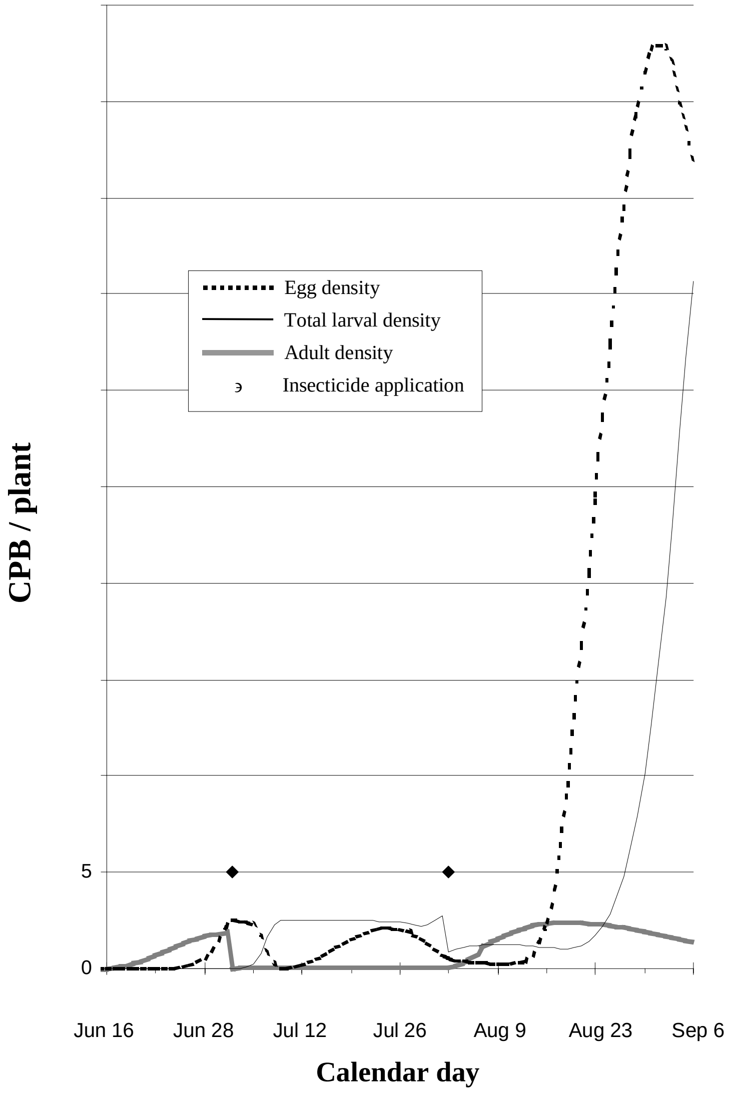


Figure 13. Simulation #21: potato beetle incidence under an application regime of rotenone on Julian day 184 (Rot-184) and Bacillus thuringiensis on Julian day 215 (Bt-215).

Currently, *Agrelation* is a deterministic model; that is, identical output is generated from identical input each time a simulation is run. The addition of stochasticity to some of the existing modules and parameters might help users identify the range of possible production scenarios for any given season. Specifically, the climate module could be augmented to generate randomized data for user-definable latitude, longitude, and elevation values. The simulation module might then be altered to run collections of simulations—changing the climate input for each simulation and reporting summarized results for a series of sequential runs.

Summary

The highly interactive, hierarchical, and modular design of *Agrelation* targets a wide range of users and uses. The interchangeable database file allows replication of simulation scenarios on more than one computer. If *Agrelation* is used for educational purposes, students might be required to parameterize several simulations and submit homework assignments in the form of a database file. Conversely, possible simulation scenarios can be distributed as database files to *Agrelation* users—be they students, producers, or others involved with agriculture. The design emphasis on user-definable input of simulation parameters enhances the ability of *Agrelation* to be Maine farm-specific, as well as specific to farms in other potato producing regions.

Agrelation was designed using an interdisciplinary approach, utilizing information from a range of fields including, but not limited to, entomology, soil science, plant science, water chemistry, chemical transport and fate, agricultural economics, environmental ethics, computer science, and biological population modeling. Graphical user interfaces and object oriented computer programming technology make interdisciplinary, modularized, and user-friendly modeling tangible and practical, thereby facilitating more holistic approaches to agricultural simulation. This work may help to bring about more sustainable farm management incorporating key factors such as environmental quality concerns and their interrelationships.

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