A simulation modeling approach to aid research into the control of a stalk-borer in the South African Sugar Industry

by

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Abstract

The control of the African stalk borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae) in sugarcane fields of KwaZulu-Natal, South Africa has proved problematical. Researchers at the South African Sugarcane Research Institute (SASRI) have since 1974 been intensively investigating various means of controlling the pest. Among the methods of control currently being investigated are biological control, chemical control, production of more resistant varieties and crop management. These investigations, however, require many years of experimentation before any conclusions can be made. In order to aid the research currently being carried out in the Entomology Department at SASRI (to investigate biological control strategies, insecticide application strategies and the carry-over decision), a simulation model of *E. saccharina* growth in sugarcane has been formulated. The model is cohort-based and includes the effect of temperature on the physiological development of individuals in each life-stage of the insect. It also takes into account the effect of the condition of sugarcane on the rate of *E. saccharina* infestation, by making use of output from the sugarcane growth model CANEGRO.

Further, a crop damage index is defined that gives an indication of the history of *E. saccharina* infestation levels during the sugarcane's growth period. It is linked to the physiological activity of the borer during the period spent feeding on the stalk tissue. The damage index can further be translated into

length of stalks bored and hence the percentage of the stalk length bored can be calculated at each point in the simulation using the total length of stalks calculated in the CANEGRO model. Using an industry accepted relationship between percent stalks damaged and reduction in sucrose content of the crop, reductions in losses in the relative value of the crop when the various control measures are implemented can be compared.

Relationships between the reduction in percent stalk length bored (and hence gains in the relative value of the crop) and the various control strategies are obtained.

Preface

The research work presented in this thesis was carried out under the supervision of Prof J W Hearne and co-supervised by Prof P Sibanda, Dr D E Conlong and Dr J Apaloo.

The work was mostly carried out in the School of Mathematical Sciences, University of KwaZulu-Natal with short stints at the South African Sugarcane Research Institute, Mount Edgecombe for consultations with entomologists and agronomists. Part of the work presented in Chapter 3 and part of the results presented in Chapter 6 have been published in the journal *Agricultural Systems* (see Horton et al, 2002).

The studies represent original work by the author and have not been submitted in any form to another university. Where use has been made of the work of others, it has been duly acknowledged in the text.

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To everyone at the Agronomy Department of SASRI who helped with CANEGRO, I owe you a lot. To Dr Carel Bezuidenhout, thanks for your patience and help. A lot of the simulations in this project required input from CANEGRO and without your help, this project would not be where it is today. Thanks.

Finally, thanks to everyone at the School of Mathematical Sciences in Pietermaritzburg for providing an environment that was pleasant to work in.

Financial support from South African Sugar Association is also gratefully acknowledged.

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List of variables and parameters

The variables and parameters are listed in the order of first appearance in the text.

e/100s	the number of *E. saccharina* large larvae and pupae per 100 stalks of sugarcane
$EGG_i(t)$	the number on day t of members in the *E. saccharina* cohort of eggs that began on day i
$SLV_i(t)$	the number on day t of members in the *E. saccharina* cohort of small larvae that began on day i
$LLV_i(t)$	the number on day t of members in the *E. saccharina* cohort of large larvae that began on day i
$PP_{i,j}(t)$	the number on day t of members in the *E. saccharina* cohort of pupae that matured from $LLV_i(j)$ on day j
$MTH_{i,j,k}(t)$	the number on day t of members in the *E. saccharina* cohort of moths that matured from $PP_{i,j}(k)$ on day k
$DD_i^{\text{stage}}(t)$	the physiological age on day t (in degree-days) of *E. saccharina* cohort i population at stage e = egg, sl = small larva, ll = large larva and p = pupa

$DD_{\min}^{\text{stage}}$ the minimum physiological age (in degree-days) required for members of an *E. saccharina* cohort population at stage e = egg, sl = small larva, ll = large larva and p = pupa to begin metamorphosis to the next stage

$DD_{\max}^{\text{stage}}$ the physiological age (in degree-days) by which all members of an *E. saccharina* cohort population at stage e = egg, sl = small larva, ll = large larva and p = pupa will have metamorphosed to the next stage

$E_i^d(t),\ E_i^m(t)$ the fraction on day t of cohort i of *E. saccharina* eggs that die or mature to the next stage, respectively

$SL_i^d(t),\ SL_i^m(t)$ the fraction on day t of cohort i of *E. saccharina* small larvae that die or mature to the next stage, respectively

$LL_i^d(t),\ LL_i^m(t)$ the fraction on day t of cohort i of *E. saccharina* large larvae that die or mature to the next stage, respectively

$P_{i,j}^d(t),\ P_{i,j}^m(t)$ the fraction on day t of members of $PP_{i,j}(t)$ that die or mature to the next stage, respectively

$M_{i,j,k}^d(t)$ the fraction of members of $MTH_{i,j,k}(t)$ that die on day t

$MDYS_{\max}$ the maximum number of days an adult *E. saccharina* moth can live

$EGG_{\text{ini}}(t)$ number of eggs used in initializing the model

$EGGLD_{i,j,k}(t)$ the number of viable eggs laid by moth cohort $MTH_{i,j,k}(t)$ on day t

$O_{i,j,k}(t)$ the oviposition rate of $MTH_{i,j,k}(t)$ on day t

d_{stage} the stage-specific mortality rates for stages e = egg, sl = small larva, ll = large larva, p = pupa and m = moth

$\varsigma(t)$ the crop water stress index on day t

ρ the resistance rating of a crop indicating susceptibility of crop to attack by *E. saccharina*

$T(t)$ the temperature on day t

$^{\circ}\text{C} \cdot \text{d}$ a measure of physiological age in degree-days

$T_{\text{th}}^{\text{stage}}$ the stage-specific threshold temperatures of development for *E. saccharina* stages e = egg, sl = small larva, ll = large larva and p = pupa

$T_{\text{ave}}(t)$ the average temperature on day t

$QLIND_{i,j}$ the quality of life index for $MTH_{i,j,k}(t)$

$ELR(n)$ the *E. saccharina* egg laying rate for moths that are n days old

$MGT_i(t)$ the number on day t of members in the *S. parasitica* cohort of maggots that began on day i

$SPP_i(t)$ the number on day t of members in the *S. parasitica* cohort of pupae that began on day i

$FLY_i(t)$ the number on day t of members in the *S. parasitica* cohort of flies that began on day i

$DD_i^{\text{mg}},\ DD_i^{\text{spp}}$ the physiological age in °C·d of the corresponding *S. parasitica* maggot and pupa cohort, respectively

$MGT_i^d(t),\ MGT_i^m(t)$ the fraction on day t of members of cohort i of *S. parasitica* maggots that die or mature to the next stage, respectively

$SPP_i^d(t),\ SPP_i^m(t)$ the fraction on day t of members of cohort i of *S. parasitica* pupae that die or mature to the next stage, respectively

$FLY_i^d(t)$ the fraction of members of cohort i of *S. parasitica* flies that die on day t

$DD_{\text{min}}^{\text{mg}},\ DD_{\text{max}}^{\text{mg}}$ the minimum and maximum physiological age required to complete the *S. parasitica* maggot stage, respectively

$DD_{\text{min}}^{\text{spp}},\ DD_{\text{max}}^{\text{spp}}$ the minimum and maximum physiological age required to complete the *S. parasitica* pupa stage, respectively

$p_{i,t}(t)$ the total number of members of $LLV_i(t)$ that have been parasitized on day t

$d_{\text{mg}},\ d_{\text{spp}},\ d_{\text{mg}}$ the stage specific mortality rates of *S. parasitica*

$T_{\text{th}}^{\text{mg}}$, $T_{\text{th}}^{\text{mg}}$	the stage-specific threshold temperatures of development for *S. parasitica*
$O(FLY_i(t))$	the oviposition rate for *S. parasitica* fly cohort i
$PARLOSS_i(t)$	the total number of members of $LLV_i(t)$ lost to parasitism
$PMR_i(t)$	the mortality rate of $LLV_i(t)$ due to parasitism
$D_{\text{ind}}(t)$	the crop damage index on day t
$SLB(t)$	the length of stalk bored on day t
σ	the stalk length bored (in mm) per large larvae per $^{\circ}\text{C} \cdot \text{d}$
$\%SLB(t)$	the percent stalk length bored on day t
ERC	estimated recoverable crystal
RV	recoverable value
S, N, F	the percent sucrose, non-sucrose and fibre present in sugarcane, respectively
t_{c}, t_{o}	mill closure and re-opening times, respectively
d_{maxeff}	duration of maximum insecticide effect (in days)
$MTH_{i,j,k}^{p}(t)$, $PP_{i,j}^{p}(t)$	the number on day t of field p moths in the moth cohort that began on day k from $PP_{i,j}^{p}(k)$ where $PP_{i,j}^{p}(t)$ is the number on day t of field p pupae
$MTH_{i,j,k}^{pq}(t)$	the number of on day t of those members of $MTH_{i,j,k}^{p}(t)$ that migrate to field q
$EGG_{i}^{pq}(t)$	the number of eggs coming from $MTH_{i,j,k}^{pq}(t)$ on day t
$MIGF^{pq}$	the natural moth migration rate from field p to field q when all field parameters are equivalent

Chapter 1

Background

1.1 The South African sugar industry

The South African sugar industry is one of the world's leading cost competitive producers of high quality sugar. It is a proceeds sharing partnership between millers and growers, established in 1935 and consisting of two members: the South African Cane Growers Association and the South African Sugar Millers Association Limited, collectively known as the South African Sugar Association (SASA). SASA combines the agricultural activities of sugarcane cultivation with the industrial factory production of raw and refined sugar, syrups, specialised sugars, and a range of by-products (Anonymous, 2003).

South African sugarcane is produced in areas extending from Northern Pondoland in the Eastern Cape Province through the coastal belt and midlands of KwaZulu-Natal to the Mpumalanga Lowveld. About 68% is grown within 30 km of the coast and 17% in the high rainfall area of the KwaZulu-Natal midlands. The balance is grown in the northern irrigated areas which comprise Pongola and Mpumalanga lowveld (Anonymous, 2003).

Direct income generated by the South African sugar industry is estimated at about ZAR6 billion (about US $870 million) per annum and contributes about ZAR2 billion (about US $190 million) to South Africa's foreign exchange earnings (`http://www.sugar.org.za`, Jan 2008). The industry has provided much needed employment not only for people from the sugar growing areas but for immigrant workers as well. Within the industry, employment totals about 85 000 jobs. Total direct and indirect employment has benefited about 350 000 people, whilst about a million people are dependent on the sugar industry. There are about 47 000 registered sugarcane growers in South Africa (`http://www.sugar.org.za`, Jan 2008).

A threat to the industry's profit margins has been losses in sucrose production due to damage caused by the stalk borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae). It has been a serious pest of sugarcane in the sugarcane growing areas of South Africa since 1971 (Atkinson, 1979; Atkinson, 1980). A recent estimate of the damaging nature of the insect to South African sugarcane was placed at between US$12 million and US$19 million in lost revenue for the 2000/2001 season (Butterfield, 2002). In some parts of the

KwaZulu-Natal sugarcane regions, damage due to the pest has been recorded to have been so serious that consignments of sugarcane were rejected when brought to the mill. Ratoon failure after harvest, due to serious damage by the pest has also been reported (Atkinson and Carnegie, 1989). In the next section, the pest *Eldana saccharina* is introduced and a review of its history, dynamics and behaviour on sugarcane in South Africa is given.

1.2 The pest *Eldana saccharina* Walker

Eldana saccharina is indigenous to Africa, where it occurs naturally in numerous wetland sedges and indigenous grasses (Girling, 1972; Atkinson, 1979; Atkinson, 1980; Conlong, 1994b). It has been a pest of graminaceous crops in other parts of Africa for over 135 years, first being described in 1865 in sugarcane in Sierra Leone (Walker, 1865). It has also been recorded in maize and sorghum (Conlong, 1994a).

The shift by *E. saccharina* from its indigenous hosts to utilizing crop plants as hosts was postulated to have occurred because the crop plants were cultivated in swampy areas containing many of *E. saccharina* hosts, placing these crops in contact with the insect (Atkinson, 1980). Because of the increased use of nitrogen and potassium fertilizers in crop production, the quality of crops has greatly improved, making them more attractive hosts (Atkinson, 1980). It has also been hypothesized that the morphology of the crop host (by providing cryptic oviposition sites) and the behaviour of the female moth, by

placing its eggs in hidden positions using its prehensile ovipositor (Conlong, 1994b; Conlong, 1997), enabled it to successfully colonize the new crop hosts. The inability of existing natural enemies to successfully find the *E. saccharina* life stages hidden cryptically in the new host plants may have further helped the insect to establish on them (Conlong, 1997).

1.2.1 Outbreak history in southern Africa

In the sugarcane growing regions of South Africa, *E. saccharina* was first recorded in sugarcane in the Umfolozi area between 1939 to around 1950 (Atkinson, 1979; Atkinson, 1980). A quiet period ensued until 1970 when it reappeared in the Hluhluwe area (Atkinson, 1979; Atkinson, 1980). Since then, *E. saccharina* has become a serious pest of sugarcane in the sugarcane growing regions of eastern Southern Africa (Atkinson, 1979; Atkinson, 1980). Figure 1.1 shows the sugar growing regions of Southern Africa and a history of *E. saccharina* outbreaks.

1.2.2 *E. saccharina* on sugarcane

Atkinson and Carnegie (1989) give a detailed account of the various stages in the life cycle of *E. saccharina*. Its life cycle on sugarcane is shown schematically in Figure 1.2. The cryptic nature of the different life stages of *E. saccharina* living on sugarcane is well described by Dick (1945) and Carnegie

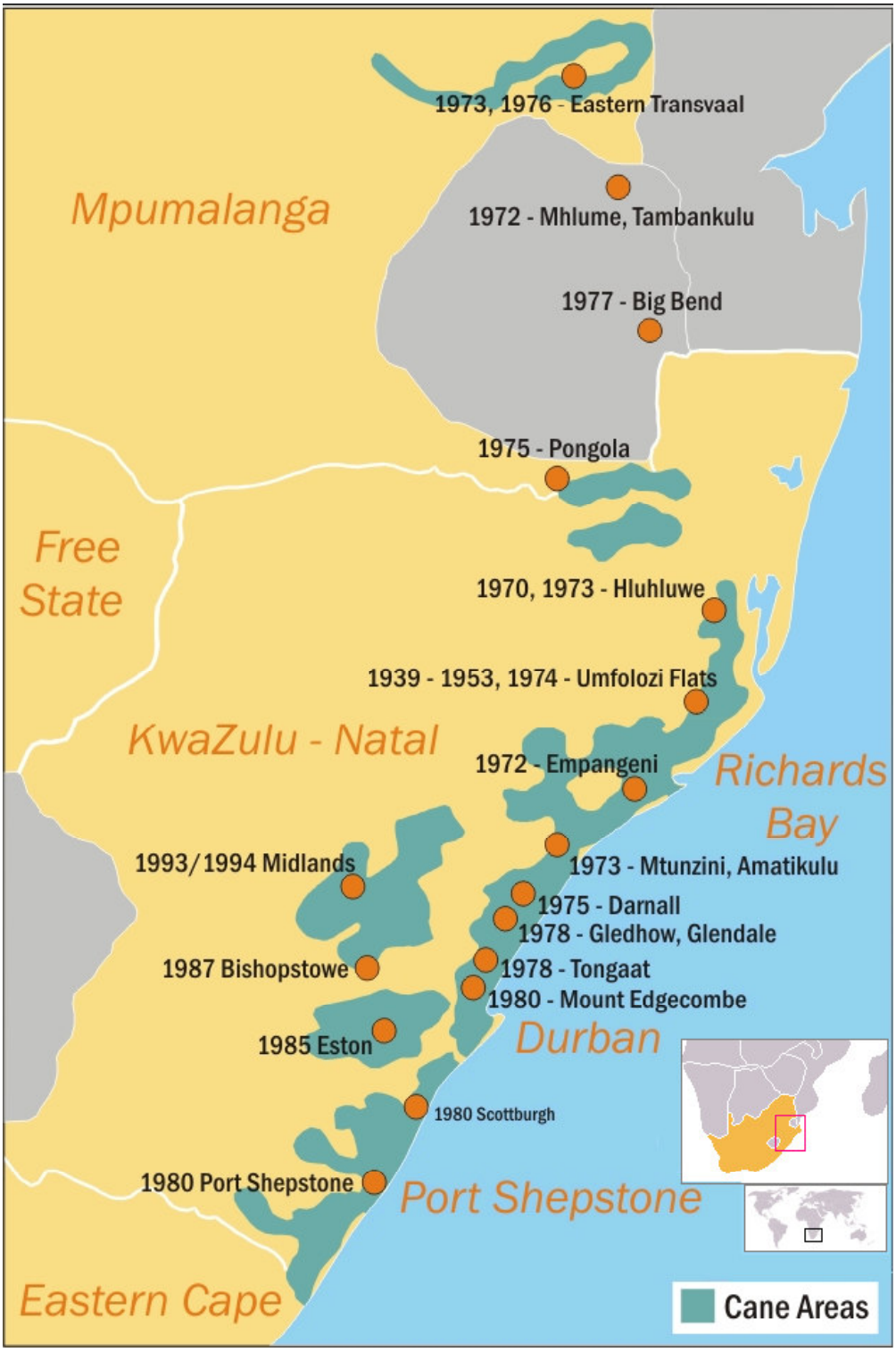

Figure 1.1: The sugarcane growing regions of southern Africa and the history of *E. saccharina* outbreaks. Year of first occurrence is given before each area affected. Source: SASRI.

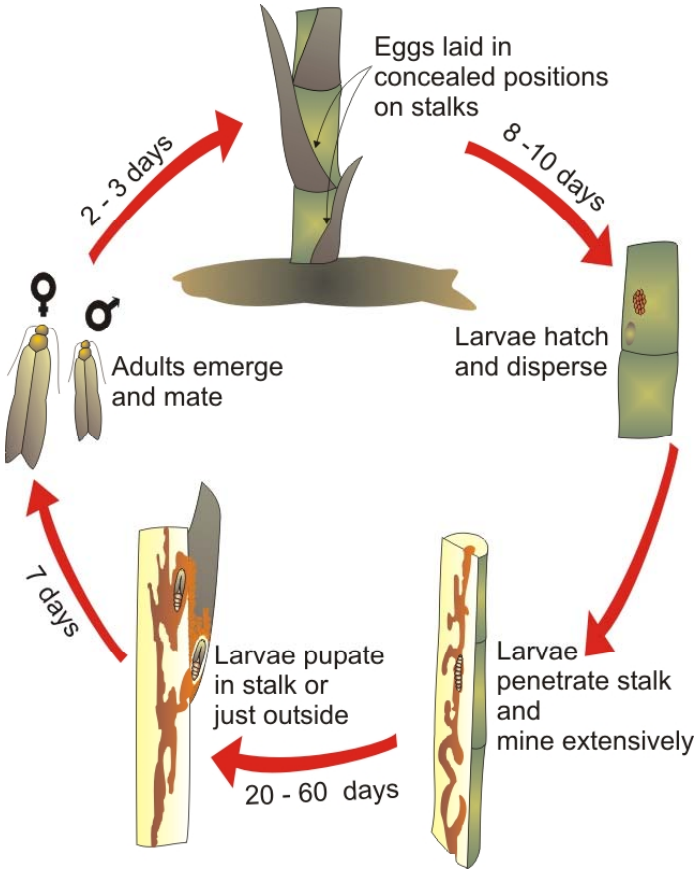

Figure 1.2: The life cycle of *E. saccharina* on sugarcane. Source: SASRI.

(1974) . Adult females cryptically place their eggs on the lower third of the cane plant, amongst the trash and between dry leaf sheaths (Conlong and Hastings, 1984; Leslie, 1990). Four to seven days later, the eggs hatch and the neonate larvae disperse from the oviposition sites. It is during this dispersal period (apart from adult dispersal, mating or oviposition periods) that the pest is most exposed. This makes the young larvae suitable targets for control measures such as insecticide application (Heathcote, 1984) or pre-trashing (Carnegie and Smaill, 1982). The neonate larvae feed initially as

scavengers on the outside of the sugarcane stalk but are protected by the dead leaf sheaths. They then bore into the stalk and for the remainder of their active larval period, they feed on the internal tissues of the stalk. It is this feeding that causes yield losses in sugarcane. *E. saccharina* infestation is usually indicated by the presence of frass (or feeding waste) appearing on the outside of the stalk. In addition to its characteristic boring, stalk damage due to *E. saccharina* is also indicated when certain portions of the stalk around the borings turn red. The percent stalk red can give an indication of losses in the amount of recoverable sucrose in the crop.

When mature enough, the larva spins a cocoon and spends an inactive pupal stage either inside the sugarcane stalk or on the outside, usually behind a leaf sheath, getting ready to ecdyse as an adult moth. Moths usually mate on the first night after emergence from pupae (Sampson and Kumar, 1985). Eggs are laid from the second night and this occurs continuously over the next 4 days (Sampson and Kumar, 1985).

The severity of *E. saccharina* infestations on sugarcane depends on the susceptibility of the crop variety to attack by the pest (e.g. Bond, 1988; Nuss et al., 1986), the age of the crop (e.g. Girling, 1978) and crop water stress (e.g. Atkinson and Nuss, 1989). Crop water stress is a key factor in borer survival. Crops that are water stressed use up less nitrogen for growth. The excess nitrogen however remains in the stalk, resulting in increased borer survival and biomass (Nuss et al., 1986; Atkinson and Nuss, 1989). The larval biomass in water stressed sugarcane can be three to five times than in well-watered

sugarcane (Nuss et al., 1986). Susceptible varieties which are water stressed are therefore at increased risk and should be harvested early.

In sugarcane, *E. saccharina* infestation is commonly expressed as the number of large larvae (and pupae) per 100 stalks (denoted e/100s and referred to as 'eldana per hundred stalks'). Management decisions by farmers rely on field surveys to determine the number of *E. saccharina* larvae found for every 100 stalks sampled. A field with more than 10e/100s is considered severely infested and harvesting is usually recommended.

Crop and sucrose losses incurred due to *E. saccharina* infestation have been estimated at about 0.1% loss in recoverable sucrose for every 1% sugarcane stalks bored (Smaill and Carnegie, 1979) and between 1.0 to 1.5 percent loss in recoverable sucrose for every 1% stalks red (Leslie and Way, 2002). A recent estimate by Butterfield (2002) indicates that during the 2001/2002 milling season, the South African sugar industry lost between R97.4 million and R150 million in revenue due to damage caused by *E. saccharina*. The *E. saccharina* problem is thus of major concern among sugarcane farmers, and means of effectively managing the pest are the subjects of intensive research programmes at the South African Sugarcane Research Institute (SASRI).

1.2.3 Pest management

In an effort to provide sugarcane farmers with an effective solution to the management of *E. saccharina* on their fields, SASRI has since 1974 been intensively investigating various means of controlling the pest. Research programmes include biological control, chemical control, crop management (such as early harvesting, pre-trashing and guarded use of pesticides) and varietal resistance (Carnegie, 1981; Conlong, 1994b; Leslie and Keeping, 1996; Keeping et al., 2003).

The biological control programme has yielded some very promising results as some parasitoids have been identified for possible use as biological control agents for *E. saccharina* (van Coller, 1992; Hearne et al., 1994; Conlong, 1994a; Conlong, 1994b; Conlong, 1997). Limiting constraints such as host incompatibility, climatic incompatibility, parasitizing ability, differing host behaviour in different habitats and initial host identification difficulties have been the source of lack of success in some parasitoids establishing themselves as biological control agents of *E. saccharina* (Conlong, 1997). Because of the lack of success of parasitoids establishing on *E. saccharina*, the biological control programme is still in the research phase and has not yet been recommended for use by sugarcane growers. Parasitoid release strategies have to be investigated further to improve their establishment on *E. saccharina* in sugarcane.

The cryptic nature of *E. saccharina* has also made it difficult to effectively

implement insecticide application strategies. The only vulnerable stage in the life cycle of the pest is soon after eclosion when the neonate larvae disperse making them suitable targets for insecticide application (Heathcote, 1984). The timing of implementation of these measures is, however, of critical importance as the young larvae quickly find hiding positions behind leaf sheaths from which they bore into the sugarcane stem after which they are well hidden (Leslie, 1993). The difficulty in timing insecticide application compounded by the lobby from various quarters against the use of insecticides has effectively restricted insecticide control to be carried out for investigative purposes only, and has not yet been approved for implementation by farmers.

At present, the most effective methods available to farmers for limiting the incidence of *E. saccharina* are crop management strategies and the planting of crop varieties that are resistant to attacks by the pest. Crop management involves early harvesting in non-irrigated regions where sugarcane may be water stressed. Other crop management practices may include pre-trashing to remove dry leaf material, removal of old stalks in the field and a guarded use of fertilizers containing nitrogen (Keeping et al., 2003).

1.3 Revenue from sugarcane

Until 1999, the remuneration in South Africa for sugarcane delivered to the mill was based on its sucrose content. The growers' share of the industrial

proceeds arising from sugar and molasses sales available for distribution was allocated to each grower in proportion to the quantity of sucrose delivered by that grower to the mill (Murray, 2000). The problem with this remuneration method was that the amount of sucrose recovered during the milling process is influenced by a number of crop quality factors as well as mill factory performance (Peacock and Schorn, 2002). This meant that growers with poor quality crop which did not contribute much to the overall industrial proceeds profited unfairly by being 'carried' by growers producing good quality crop (Murray, 2000).

A more equitable method of payment was adopted by the South African sugar industry from the beginning of the 2000/2001 milling season. The formula adopted is called the *relative* or *recoverable value* formula (referred to as the *RV* formula) and was developed by Murray (unpubl.). It is a modification of the *estimated recovery crystal* (usually referred to as ERC) formula proposed by van Hengel (1974). The RV formula attempts to allow for the effect of sugarcane quality on sucrose recovery, providing a more accurate measure of the real value of the sugarcane supplied to the mill.

The RV formula will be explored in greater detail in Chapter 6.

Chapter 2

Introduction

2.1 Integrated pest management systems

The growing pressure on world food supplies and environmental problems associated with the use of pesticides have triggered research into the development of new approaches and techniques aimed at improving the efficiency of pest control programs (Shoemaker, 1981; Kropff et al., 1995). Integrating the use of non-chemical means of pest control with improved timing of chemical pesticide applications has demonstrated a capacity to significantly reduce pesticide use and to increase profits (Shoemaker, 1981).

The development of effective integrated pest management systems requires detailed knowledge of the interactions between the crop and its pests in or-

der to identify points of intervention and to predict effects of the intervention through damage or yield loss relationships (Shoemaker, 1981; Kropff et al., 1995). Mathematical models have become an increasingly important tool in analysing the dynamics of these systems as they make it possible to investigate a wide variety of pest control strategies which would be economically infeasible in practice and which would require many years of experimentation (Shoemaker, 1981).

In this chapter, we give a brief review of the basic framework for models of host-parasitoid interactions and describe the approach adopted for modeling the system we are investigating.

2.2 Models of host-parasitoid interactions

According to Holling (1966) and Mills and Getz (1996), the earliest mathematical models of animal populations can be attributed to the period between 1923 and 1935 with contributions from Lotka (1923 and 1925), Thompson (1924 and 1929), Volterra (1926 and 1931) and Nicholson and Bailey (1935). A review of these models is given in Mills and Getz (1996).

The basic framework for most models of host-parasitoid interactions in use today are variations of the continuous time Lotka-Volterra model and the discrete time Nicholson-Bailey model.

The influential Nicholson-Bailey model of a discrete host-parasitoid interaction is given by the difference equations:

$$\begin{aligned} X_{t+1} &= \lambda X_t e^{-aY_t} \\ Y_{t+1} &= X_t \left\{1 - e^{-aY_t}\right\} \end{aligned} \tag{2.1}$$

where X_t and X_{t+1}, and Y_t and Y_{t+1} are the host and parasitoid populations in generations t and $t+1$ respectively, λ is the per capita net rate of growth of the host population, and the function e^{-aY_t} gives the proportion of the host population that escapes parasitoid attack with a representing the proportion of the host environment that can be covered by an individual parasitoid in its lifetime. The Nicholson-Bailey model (2.1) does not adequately describe general host-parasitoid interactions in that it assumes that every attacked host gives rise to a single parasitoid, a situation appropriate for solitary parasitoids in which only one sex is present (Mills and Getz, 1996). It also predicts the eventual extinction of the parasitoid population, a situation which is rare in host-parasitoid (and even predator-prey) interactions. Its importance lies in the fact that it has served as a basis for the development of more realistic models of discrete generation host-parasitoid interactions. A more general form of the Nicholson-Bailey model was presented by May and Hassell (1988):

$$\begin{aligned} X_{t+1} &= d(X_t) X_t f(X_t, Y_t) \\ Y_{t+1} &= c X_t \left\{1 - f(X_t, Y_t)\right\} \end{aligned} \tag{2.2}$$

where $d(X_t)$ is the per capita net rate of growth of the host population, $f(X_t, Y_t)$ is the proportion of the host population that escapes parasitoid attack, and c indicates the rate at which parasitised hosts are converted to parasitoids. The escape function $f(X_t, Y_t)$ can be formulated to include

parameters such as handling time (see, e.g., Holling, 1966) and density dependence to improve the stability of the model. The Thompson model has a structure similar to equation (2.2) with the per capita net rate of growth of the host population $d(X_t) = c = \mu$ and $f(X_t, Y_t) = e^{-\beta Y_t / X_t}$. Together with the Nicholson-Bailey model, the Thompson model made a significant advance by including a parameter (β) based on the assumption that parasitoids search randomly (Holling, 1966). It differs from the Nicholson-Bailey model in that, depending on initial population densities, it predicts that host and parasitoid populations may both crash to zero or may both grow without bound (Mills and Getz, 1996).

For overlapping host generations, a more appropriate model is the continuous-time differential equation (Lotka-Volterra) model given by

$$\begin{aligned} dX/dt &= rX - aXY \\ dY/dt &= \gamma aXY - \delta Y \end{aligned} \tag{2.3}$$

where X and Y are respectively the host and parasitoid populations, r is the per capita net rate of growth of the host population, a is the parasitoid attack rate, γ is the conversion rate of hosts to parasitoids and δ is the per capita parasitoid death rate. In order to allow for the inclusion of density dependence and various functional response classes, the Lotka-Volterra model (2.3) is generalised to (see, e.g., Mills and Getz, 1996):

$$\begin{aligned} dX/dt &= g(X)X - h(X,Y)Y \\ dY/dt &= \gamma h(X,Y)Y - \delta Y \end{aligned} \tag{2.4}$$

where $g(X)$ is the per capita net rate of growth of hosts and $h(X, Y)$ is the per capita functional response of the parasitoid. The Lotka-Volterra model (2.3) was originally developed for predator-prey systems rather than

host-parasitoid systems. It is more appropriate in situations where hyperparasitsm is not present, i.e., where the parasitoid does not parasitize hosts that have been previously attacked. This is not generally the case in host-parasitoid situations and it certainly is not the behaviour observed in the host-parasitoid interaction to be considered here (Conlong, pers. comm.). The Lotka-Volterra model (2.3) has however, despite this, been used as a basis of many host-parasitoid models when interactions with overlapping host generations are considered (Mills and Getz, 1996).

While the Nicholson-Bailey model framework and Lotka-Volterra model framework have contributed to the development and conceptual advancement for a theory of biological control, the dynamics of the host-parasitoid models developed lacked the ability to generate stable interaction with a low equilibrium host density (Mills and Getz, 1996). These features are generally considered to be characteristic of successful biological control (Mills and Getz, 1996).

Models based on the Nicholson-Bailey and Lotka-Volterra models are strong analytical tools, but important ecological parameters and complex interactions have been ignored in order to keep them simple for mathematical analysis (Axelsen, 1994). Age structure in populations has become more widely recognized as important (Li, 1990). A pest's ability to inflict crop damage and the pest's susceptibility to control measures varies considerably with age (Shoemaker, 1981). In the study of continuous age structured single species population models, the McKendrick-von Foerster partial differential equation is usually employed (Li, 1990). When age structure is introduced into

interactions of multispecies, the models can become very complex, making their analysis difficult (Li, 1990). As a result, age structure is often neglected in theoretical/analytical models.

When confronted with the problem of pest management, as is the case in this study, simulation and optimization models have been used (Shoemaker, 1981). Simulation type models can take many parameters and interactions into consideration and have been used to simulate phenology and population development (Axelsen, 1994). However, due to the complexity of biological systems, models involving all possible ecological components are often very complex and lengthy (Wilder, 1999). A simple model which is capable of emulating observed phenomena often proves useful in studying some aspects of the more complex system. While no simplified model can hope to accurately predict the results of a more complete one, simple models are often useful over broad realistic ranges and it then becomes a problem of finding the appropriate simplified model to emulate the type of behaviour one wishes to study (Wilder, 1999).

With these comments in mind and, as other researchers have remarked (Starfeld and Bleloch, 1986; Ruesink, 1982), it is important to clearly state the objectives of the study before an appropriate modeling technique and model depth can be selected.

2.2.1 Objectives of the study

The objectives of the study are as follows:

§§ To yield insight into the interactions of *E. saccharina* with the host crop sugarcane by using crop data generated by the sugarcane crop model CANEGRO (see Inman-Bamber, 1991; Bezuidenhout, 2000).

§§ To test various management strategies on the effectiveness of measures currently under investigation for the control of *E. saccharina* on sugarcane. The control measures to be considered are early and delayed harvesting, biological control, and insecticide application.

§§ To find optimal strategies for implementing the control measures.

2.2.2 The modeling approach adopted

In order to accommodate the above objectives, the phenological aspects of the insects have to be modeled. To achieve this, a detailed stage structured model is required as different stages in the development of the insect react differently to environmental conditions. A stage structured model is also very important when investigating pest management strategies as it is certain stages in the development of the insect that should be targeted for the control measures to work effectively and efficiently. For example, chemical control strategies

will require knowledge about the population of the stage most vulnerable to insecticide application (in this case, the neonate larvae during dispersal and before boring into the sugarcane stalk), while parasitoid release strategies will require knowledge about the stage targeted by the parasitoids (in this case, the large larval stage).

Because of the flexibility of computer simulation models, many pest management models are of this type. Simulation models have been used to study various systems such as disease control (e.g., Chan et al., 1994) and agricultural pest management systems (e.g., Vorley and Wratten, 1985; Axelsen, 1994; DeGrandi-Hoffman, et al., 1994; Hearne et al., 1994; O'Neil et al., 1996; Meikle, et al., 1998; Throne et al., 1998; Wilder, 1999; Horton et al., 2002). The objectives of the study determine what aspects of the system are to be modelled and to what depth.

The first attempt at modeling *E. saccharina* on sugarcane was presented in van Coller (1992) and Hearne et al. (1994). While the model gave valuable insight into the possibility of using larval and pupal parasitoids in the biological control of *E. saccharina*, it did not explicitly include the temperature effects on the development of the insects, nor were interactions with the host crop included. In reality, however, a host-parasitoid interaction never occurs in isolation of a host plant (Mills and Getz, 1996) and the condition of sugarcane is known to greatly affect the incidence of *E. saccharina* on the crop (Girling, 1978; Nuss et al., 1986; Bond, 1988; Atkinson and Nuss, 1989).

A new model that incorporates sugarcane dynamics and explicitly models temperature effects on the development of *E. saccharina* was therefore required. In this study, we first develop a pest model to interact with an existing sugarcane model to determine crop damage due to the pest, and also to investigate harvesting decisions especially for late planted crops (we will discuss the meaning of late planted crops in a later chapter) and the effect of insecticide application strategies on the harvest decision. We then extend the model to include host-parasitoid interactions and investigate larval parasitoid release strategies.

Before we proceed with model formulation, we give a very brief description of the CANEGRO model for sugarcane production and its output that will be relevant for the *E. saccharina* model on sugarcane.

2.3 The CANEGRO model

The CANEGRO sugarcane production simulation model which was reviewed by Bezuidenhout (2000) is a mechanistic model which describes environmental, physiological and managerial features of the agricultural sugarcane production system. Atmospheric conditions such as temperature, solar radiation and evapotranspiration and soil conditions such as soil type, layer thickness, soil water content and others are used to model various aspects of the plant's phenology.

For the purposes of this study, the CANEGRO outputs that will be used are crop water stress (*E. saccharina* infestation levels are linked to crop water stress - Atkinson and Nuss, 1989), dead leaf numbers (*E. saccharina* lays its eggs on dry leaf matter - Conlong and Hastings, 1984; Lelsie,1990) and stalk height to calculate percent stalks damaged.

We now proceed to formulate the *E. saccharina* model.

Chapter 3

Model formulation

3.1 Introduction

In this chapter, we present a detailed description of the *E. saccharina* population model (hereafter referred to as "the model") used to test various management strategies to control the pest. This forms the basis for the host-parasitoid model presented in Chapter 4 as well as the spatial model presented in Chapter 8. It is an extension of the model developed by Horton et al. (2002) and is designed to take into account the condition of sugarcane as host crop (see Horton et al., 2000). Crop condition as used in the model is a combination of three factors: crop resistance rating, the number of dead leaves per stalk and crop water stress. Crop resistance rating is a variety specific index (determined at SASRI) which indicates the susceptibility of

the crop variety being investigated to *E. saccharina* infestation. The number of dead leaves per stalk is used to model the number of sites available for egg laying since *E. saccharina* moths have a preference to oviposition on dry cane leaf material (Leslie, 1990; Carnegie and Smaill, 1982). Soil water deficit is used to model crop water stress which indicates the severity of potential attack on the crop by the pest since *E. saccharina* thrives on stressed sugarcane (Atkinson and Nuss, 1989). Atkinson and Nuss (1989) recorded an increase in Nitrogen content in water stressed sugarcane resulting in increased larval survival rates and biomass. Moths emerging from such larvae have been recorded to have increased fecundity rates (e.g. Shanower et al., 1993b).

The sugarcane growth model, CANEGRO described in Inman-Bamber (1991) and Bezuidenhout (2000) is used to determine the number of dead leaves per stalk and crop water stress. This is achieved via a dynamic link between the model and CANEGRO (see Figure 3.1).

3.2 Description of the model

For the purposes of the model, the larval stage in the *E. saccharina* life cycle (Figure 1.2) is divided into two so that the model has five distinct stages, namely, the egg, small larva (consisting of instars I - III), large larva (consisting of instars IV and above), pupa and moth (or adult) stages. The reason for having two larval stages is threefold. Firstly, crop damage is

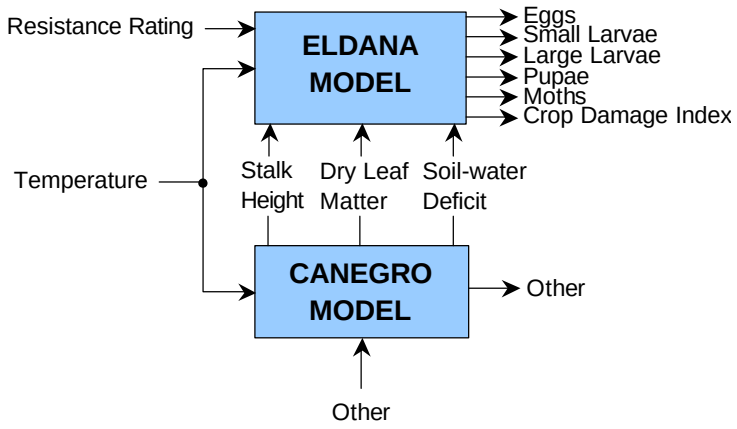

Figure 3.1: *E. saccharina* model interaction with the CANEGRO model.

done by the larger larvae. Also, the large larvae feed on the part of the stalk that contains sucrose. Information on the numbers of these over time will aid in determining crop damage and sucrose reduction. Secondly, when investigating insecticide application strategies, information on numbers of small larvae will be needed since this is the only stage in the *E. saccharina* life cycle (apart from adult stage) that is exposed and hence makes it a suitable target for insecticide control (Heathcote, 1984). Thirdly, the quality of the stalk that the large larvae feed on has an impact on the fecundity of the resultant moths (e.g. Shanower et al., 1993b) and so we need to keep a record of the crop quality for the duration of this stage (i.e. "quality of life").

In order to monitor population numbers in each stage of the *E. saccharina* life cycle more accurately, the model is structured in such a way that the

stages are further subdivided into a number of cohorts. Since the model is based on a daily time-step (i.e. the model updates *E. saccharina* population numbers on a daily basis), a cohort refers to a group of individuals that enter a particular stage on the same day. Cohorts in the egg, small larva and large larva stages are distinguished only by the day on which they began. For these stages there cannot be two different cohorts that began on the same day. For example, all eggs laid on a particular day are grouped into one cohort.

As soon as large larvae metamorphose into pupae, the cohort structure changes. In addition to entering the pupa stage on the same day, members of a pupa cohort are required to come from no more than one cohort of large larvae. This means that one cohort of large larvae can result in a number of pupa cohorts distinguished by the day on which those members pupated. Pupa cohorts sharing a larval cohort as a "parent" are distinguished by the day on which those members of the "parent cohort of large larvae" metamorphose into pupae (metamorphosis generally does not occur all at once). Thus, a pupa cohort is identified by the day on which it began and the cohort of large larvae it came from. This is done in order to carry information on the "quality of life" of the larvae onto the resulting moth cohort because there is evidence that this has an impact on the fecundity of the moths (Conlong, pers. com.). The "quality of life" refers to the nitrogen in the crop (indicated by crop water stress) experienced during the larval stage and this would differ from cohort to cohort.

Moth cohorts are set up in a similar manner by taking into account the day

they begin and the pupa cohort they come from. Again, this is done to be able to keep track of the "quality of life" experienced in the larval stage.

Monitoring cohorts in this way has the advantage of giving insight into the physiological age composition of each stage, which aids in calculating numbers that mature to the next stage on any given day. For example, the total egg population on any given day is made up of many egg cohorts of differing chronological age. Only eggs from cohorts that have reached sufficient physiological age for hatching will contribute to the formation of a cohort of small larvae on that day.

Since the time spent in each stage of the *E. saccharina* life cycle is temperature dependent, the physiological age of a cohort is a measure of the number of degree-days ($^{\circ}\mathrm{C} \cdot \mathrm{d}$) accumulated above a threshold temperature for growth. Maturation from one stage to the next occurs when the physiological age of the cohort reaches the sufficient number of degree-days required for that stage.

When the model is run, driven by output data from the CANEGRO model, the first *E. saccharina* egg cohort is introduced the day when CANEGRO indicates the availability of dead leaves. The model assumes that new eggs are laid on a daily basis by moths that are "lingering about" from nearby fields until the system generates its own moths. As soon as the model has its own moths, they take over the creation of new egg cohorts. Egg cohorts created by immigrant moths from neighbouring fields (as in the initialization) will

be considered only if no egg cohorts are created by the system's own moths. The model assumes that no other stages in the *E. saccharina* life cycle are present when the initial egg population is introduced.

On any given day, some of the eggs in egg cohorts that have reached sufficient physiological age (in $°C \cdot d$) hatch out as small larvae. The aggregate of all small larvae hatching out from all of the egg cohorts in existence on that day forms a cohort of small larvae. Thus, in general, the newly formed cohort of small larvae consists of individuals from more than one egg cohort.

In due course, once sufficient time has passed and the cohort of small larvae has reached the right physiological age, individuals begin to bore into the cane stalk as large larvae. All small larvae that bore into the cane stalk on the same day form a cohort of large larvae. When a cohort of large larvae reaches a certain physiological age, individuals begin metamorphosis into pupae and form pupal cohorts. As stated earlier, a pupal cohort will result from a particular large larva cohort that metamorphosed on that day. This means that we may have more than one pupal cohort that began on that day, the distinguishing factor being the large larva cohort they came from. By a similar process moth cohorts are formed distinguished by the pupal cohort they came from and the day they began. The whole cycle then repeats. The creation and demise of cohorts is shown schematically in Figure 3.2.

The model has a daily time step and thus new cohorts are formed once a day. Once a cohort has come into existence it does not receive any further

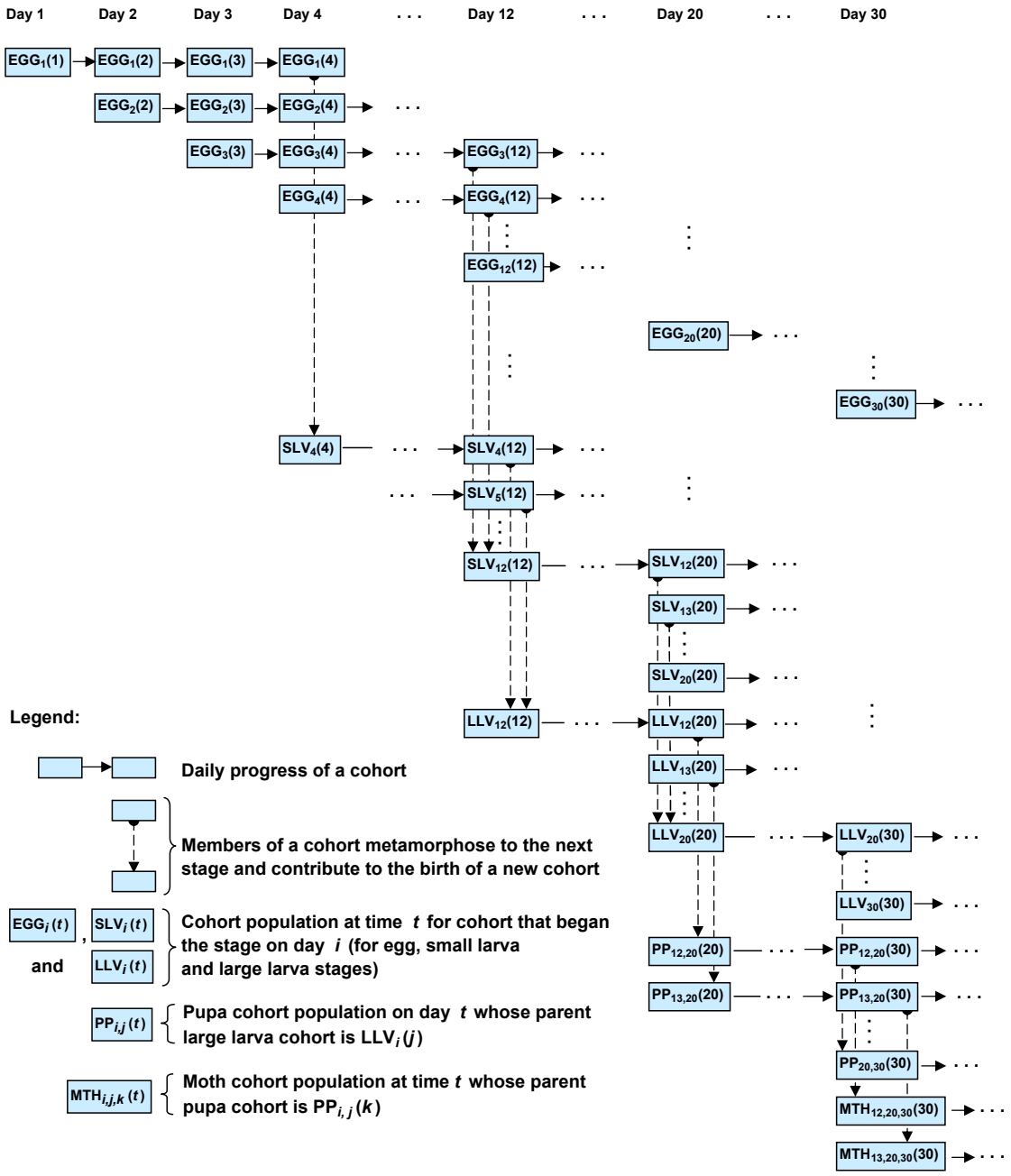

Figure 3.2: The interaction between various cohorts in the model showing how older cohorts contribute to the birth of new cohorts.

recruits on later days. Some members of a typical cohort may die during any given day. These individuals are removed from the system during the daily update.

A record in a database represents each cohort. Various fields in the record keep track of information such as the day when a cohort came into existence, the number of individuals in the cohort, the "quality of life" during its large larval stage and its physiological age. When updating takes place each day, all fields, i.e. all attributes of each cohort are adjusted. This must be done separately for all of the cohorts. The updating process includes the determination of mortality numbers and numbers maturing onto the next life stage. The calculations are based on a set of functions using for arguments, certain fields in the record representing the cohort.

In the following section, a detailed mathematical representation of the model is presented.

3.3 Mathematical description of the model

For readability we introduce notation that differs from that in Horton et al. (2002). Let $EGG_i(t)$, $SLV_i(t)$ and $LLV_i(t)$ represent, respectively the number, on day t, of members in the egg, small larva and large larva cohort that began that particular stage on day i. Thus $EGG_i(t)$ represents the

number on day t of eggs that were laid on day i. Let $PP_{i,j}(t)$ represent the number of members on day t in the pupa cohort that started out on day j from the large larva cohort $LLV_i(j)$. Finally, let $MTH_{i,j,k}(t)$ represent population of the moth cohort that began on day k from the pupa cohort $PP_{i,j}(k)$.

Let $DD_i^{\mathrm{e}}(t)$, $DD_i^{\mathrm{sl}}(t)$, $DD_i^{\mathrm{ll}}(t)$ and $DD_{i,j}^{\mathrm{p}}(t)$ represent the physiological age, at time t, in degree-days ($^\circ\mathrm{C} \cdot \mathrm{d}$) of the corresponding egg, small larva, large larva and pupa cohorts, respectively. Also let $DD_{\min}^{\mathrm{e}}$, $DD_{\min}^{\mathrm{sl}}$, $DD_{\min}^{\mathrm{ll}}$ and $DD_{\min}^{\mathrm{p}}$ denote the minimum physiological age at which members of a cohort in the egg, small larva, large larva and pupa stage respectively begin to move onto the next stage. Similarly, let $DD_{\max}^{\mathrm{e}}$, $DD_{\max}^{\mathrm{sl}}$, $DD_{\max}^{\mathrm{ll}}$ and $DD_{\max}^{\mathrm{p}}$ denote the physiological age by which all members of a cohort in the egg, small larva, large larva and pupa stage will have made the transition to the next stage. Note that in general, insects of the same physiological age will not necessarily move on to the next life stage at the same time.

We denote the fraction of members of a cohort that die on day t by $E_i^d(t)$, $SL_i^d(t)$, $LL_i^d(t)$, $P_{i,j}^d(t)$, $M_{i,j,k}^d(t)$ for the corresponding egg, small larva, large larva, pupa and moth cohort respectively. Similarly, we denote the fraction of members of a cohort that mature to the next stage on day t by $E_i^m(t)$, $SL_i^m(t)$, $LL_i^m(t)$ and $P_{i,j}^m(t)$. For indexing purposes, we define the following

sets

$$
\begin{aligned}
S_{\mathrm{e}}(t) &= \left\{t, t-1, t-2, \ldots, t-\tau_{\mathrm{e}} : DD^{\mathrm{e}}_{\tau_{\mathrm{e}}}(t) \leq DD^{\mathrm{e}}_{\max} < DD^{\mathrm{e}}_{\tau_{\mathrm{e}}-1}(t)\right\}, \\
S_{\mathrm{sl}}(t) &= \left\{t, t-1, t-2, \ldots, t-\tau_{\mathrm{sl}} : DD^{\mathrm{sl}}_{\tau_{\mathrm{sl}}}(t) \leq DD^{\mathrm{sl}}_{\max} < DD^{\mathrm{sl}}_{\tau_{\mathrm{sl}}-1}(t)\right\}, \\
S_{\mathrm{ll}}(t) &= \left\{t, t-1, t-2, \ldots, t-\tau_{\mathrm{ll}} : DD^{\mathrm{ll}}_{\tau_{\mathrm{ll}}}(t) \leq DD^{\mathrm{ll}}_{\max} < DD^{\mathrm{ll}}_{\tau_{\mathrm{ll}}-1}(t)\right\}, \\
S^i_{\mathrm{p}}(t) &= \left\{t, t-1, t-2, \ldots, t-\tau_{\mathrm{p}} : DD^{\mathrm{p}}_{i,\tau_{\mathrm{p}}}(t) \leq DD^{\mathrm{p}}_{\max} < DD^{\mathrm{p}}_{i,\tau_{\mathrm{p}}-1}(t)\right\} \quad \text{and} \\
S_{\mathrm{m}}(t) &= \left\{t, t-1, t-2, \ldots, t-\tau_{\mathrm{m}} : \tau_{\mathrm{m}} = MDYS_{\max}\right\},
\end{aligned}
$$

where $MDYS_{\max}$ is the maximum number of days an adult *E. saccharina* moth can live. The above index sets will aid in considering only the cohorts that are in existence on day t.

With the above notation, the day to day dynamics of the *E. saccharina* population in the various stages and cohorts can be modeled by the following system of difference equations:

$$
\begin{aligned}
EGG_i(t+1) &= EGG_i(t) \times (1 - E^d_i(t) - E^m_i(t)), \quad i \in S_{\mathrm{e}}(t) \\
SLV_i(t+1) &= SLV_i(t) \times (1 - SL^d_i(t) - SL^m_i(t)), \quad i \in S_{\mathrm{sl}}(t) \\
LLV_i(t+1) &= LLV_i(t) \times (1 - LL^d_i(t) - LL^m_i(t)), \quad i \in S_{\mathrm{ll}}(t) \\
PP_{i,j}(t+1) &= PP_{i,j}(t) \times (1 - P^d_{i,j}(t) - P^m_{i,j}(t)), \quad j \in S^i_{\mathrm{p}}(t) \\
MTH_{i,j,k}(t+1) &= MTH_{i,j,k}(t) \times (1 - M^d_{i,j,k}(t)), \quad k \in S_{\mathrm{m}}(t)
\end{aligned}
\tag{3.1}
$$

The initial conditions of system (3.1) are given by equations (3.2) through to (3.7):

$$EGG_t(t) = EGG_{\mathrm{ini}}(t), \tag{3.2}$$

before first moths are generated by the system

$$EGG_t(t) = \sum_{k \in S_{\mathrm{m}}(t)} EGGLD_{i,j,k}(t), \tag{3.3}$$

after system has generated its own moths and

$$SLV_t(t) = \sum_{i \in S_{\mathrm{e}}(t)} E_i^m(t) \times EGG_i(t) \tag{3.4}$$

$$LLV_t(t) = \sum_{i \in S_{\mathrm{sl}}(t)} SL_i^m(t) \times SLV_i(t) \tag{3.5}$$

$$PP_{i,t}(t) = LL_i^m(t) \times LLV_i(t), \quad i \in S_{\mathrm{ll}}(t) \tag{3.6}$$

$$MTH_{i,j,t}(t) = P_{i,j}^m(t) \times PP_{i,j}(t), \quad j \in S_{\mathrm{p}}^i(t) \tag{3.7}$$

$EGG_{\mathrm{ini}}(t)$ in equation (3.2) is the number of eggs used in the initialization process (based on the age of the crop, the time of the year and on the assumption that some moths from neighbouring fields will come in to lay their eggs when dead leaves begin to appear), while $EGGLD_{i,j,k}(t)$ in equation (3.3) is the number of viable eggs laid by moth cohort $MTH_{i,j,k}(t)$ on day t:

$$EGGLD_{i,j,k}(t) = O_{i,j,k}(t) \times MTH_{i,j,k}(t),$$

where $O_{i,j,k}(t)$ is the oviposition rate of moth cohort $MTH_{i,j,k}(t)$. Note that equation (3.3) does not include EGG_{ini}. This is because it is assumed that moth immigration into the field is cancelled out by emigration.

We discuss the death rate, the physiological age, the rate of maturation from one stage to the next and the oviposition rate in more detail in the sections that follow.

3.3.1 Stage specific mortality rates

The mortality rate of a cohort on any given day depends on the life stage that the cohort is in and also on the day's average temperature. The Entomology Department at SASRI has accumulated vast data on the stage specific mortality rates of *E. saccharina* and how temperature affects these rates. The stage specific mortality rates of *E. saccharina* (per day) at a temperature of 26°C are given in Table 3.1. The effect of temperature on these rates is given in Table 3.2.

Table 3.1: Stage-specific mortality rates (per day) for *E. saccharina* at a temperature of 26°C . Source: van Coller (1992).

	eggs (d_{e})	small larvae (d_{sl})	large larvae (d_{ll})	pupae (d_{p})	moths (d_{m})
Mortality rate (/day)	0.03	0.09	0.115	0.07	0.2

The survival rates of small larva and large larva in sugarcane are further affected by crop water stress (Atkinson and Nuss, 1989) and the ability of the crop variety to resist *E. saccharina* infestation (Keeping, pers. comm.; Carnegie, 1981).

Crop water stress is directly proportional to the level of *E. saccharina* infestation, i.e., the higher the crop water stress, the higher the incidence of *E. saccharina*. In the model, this is accounted for by decreasing larval mortality when the crop is water stressed. The decrease/increase in mortality

rate (depending on crop water stress level) is modeled by a stress multiplier function in the calculation of mortality rates for cohorts of small larvae and large larvae. Since the mortality rates given in Table 3.1 were calculated under laboratory conditions with a "normal" diet, we assume that the rates apply to intermediate stress conditions and we employ a function g_{stress} of the shape shown in Figure 3.3 (see Appendix A.3 for a description of a function with such properties) to model the effect of low to high stress on the mortality rates. (A simpler function given by $g(\varsigma) = 1 + 0.5 \cos \pi\varsigma$ can also be employed. However, this function will restrict the choice of the lower- and upper-bounds for the stress multiplier factor to 0.5 and 1.5 respectively.)

The crop water stress index used in the function shown in Figure 3.3 is an index calculated from the daily soil water deficit output of the CANEGRO model. CANEGRO does not directly calculate crop water stress, but soil water deficit is a good indicator of crop water stress. According to agronomists at SASRI, the higher the soil water deficit (given on a scale of 0 to 1 by CANEGRO), the lower the crop water stress and vice versa (Bezuidenhout, pers. comm.). The crop water index is thus calculated as the difference between 1 and the soil water deficit and is also given on a scale from 0 to 1.

Researchers at SASRI have a resistance rating system to rate crops for their resistance against *E. saccharina* infestation (e.g. Keeping et al., prep). A crop assigned a resistance rating of 5 is considered to have intermediate resistance. Each index rating above 5 indicates 15% more *E. saccharina* larval activity. As *E. saccharina* moths show no crop preference when laying

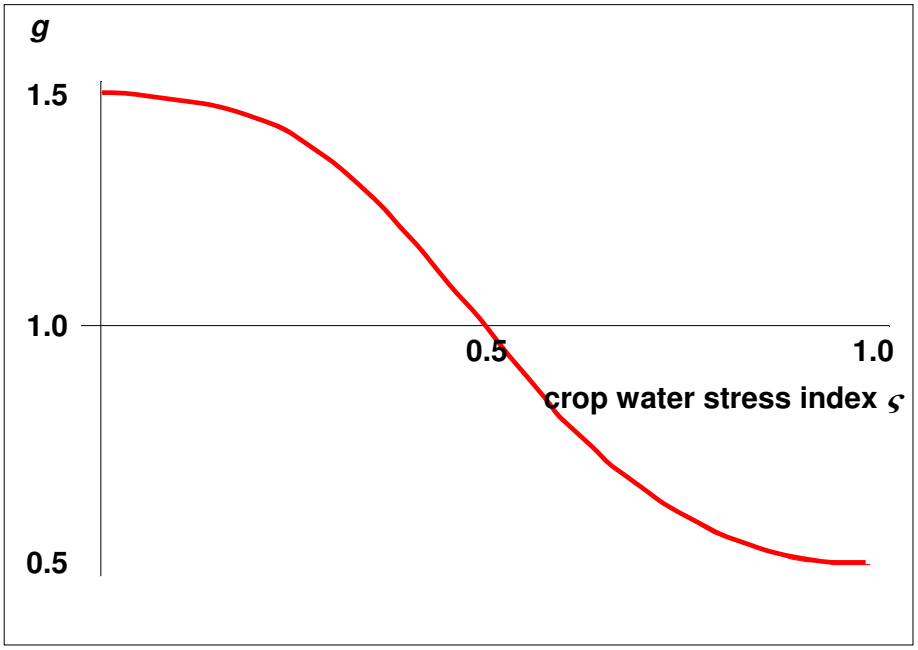

Figure 3.3: The stress multiplier function $g(\varsigma)$.

their eggs (Atkinson and Nuss, 1989), this means that larvae survival is increased by 15% for each index rating above 5. We therefore further multiply the mortality rate by a resistance rating function (R) to account for this increase/decrease in *E. saccharina* activity.

Let d_{e}, d_{sl}, d_{ll}, d_{p} and d_{m} represent the stage specific mortality rates (given in Table 3.1) of eggs, small larvae, large larvae, pupae and moths, respectively. Denote the crop water stress on day t of the simulation by $\varsigma(t)$. Let ρ denote the resistance rating index of the crop under consideration. Then, on any given day, the fraction of members of a cohort that die is given by the

equations

$$E_i^d(t) = d_{\mathrm{e}} \times f_{\mathrm{e}}(T(t)) \tag{3.8}$$

$$SL_i^d(t) = d_{\mathrm{sl}} \times f_{\mathrm{sl}}(T(t)) \times g_{\mathrm{stress}}(\varsigma(t)) \times R(\rho) \tag{3.9}$$

$$LL_i^d(t) = d_{\mathrm{ll}} \times f_{\mathrm{ll}}(T(t)) \times g_{\mathrm{stress}}(\varsigma(t)) \times R(\rho) \tag{3.10}$$

$$P_{i,j}^d(t) = d_{\mathrm{p}} \times f_{\mathrm{p}}(T(t)) \tag{3.11}$$

$$M_{i,j,k}^d(t) = d_{\mathrm{m}} \times f_{\mathrm{m}}(T(t)) \tag{3.12}$$

where the temperature functions f_{e}, f_{sl}, f_{ll}, f_{p} and f_{m} are determined by finding the lowest degree polynomial that gives a satisfactory fit to the corresponding stage data in Table 3.2. The data of Table 3.2 come from laboratory experiments in which mortality rates at various temperatures where monitored for the different life stages of *E. saccharina*. Whilst the insect was found to be less active at temperatures below 10°C, it should also be noted that temperatures in the regions under study rarely fall below 10°C or rise above 30°C and so the collocation points given in Table 3.2 should be sufficient to model changes in the mortality rates of the various *E. saccharina* stages.

Table 3.2: Collocation points for the temperature functions used to adjust mortality rates. Source: SASRI.

	10°C	19°C	22°C	26°C	30°C
eggs	0.00	0.64	0.78	1.00	1.10
small larvae	0.00	0.58	0.78	1.00	1.10
large larvae	0.00	0.58	0.78	1.00	1.10
pupae	0.00	0.44	0.54	1.00	1.10
moths	0.00	0.56	0.71	1.00	1.10

3.3.2 Physiological age

The rate of insect development depends on the temperature to which the insect is exposed. The temperature below which no measurable development occurs is known as the threshold temperature of development and can vary from stage to stage in the insect's lifecycle. Insect development (i.e. the physiological age of the insect) is measured as the number of *day-degrees* ($^{\circ}\mathrm{C} \cdot \mathrm{d}$) accumulated above the threshold temperature of development. The total number of $^{\circ}\mathrm{C} \cdot \mathrm{d}$ required to complete some aspect of development (e.g. a stage of development in the insect's lifecycle) is considered to be a thermal constant.

Many methods for calculating $^{\circ}\mathrm{C} \cdot \mathrm{d}$ have been developed (see Pruess, 1983 for a review of the commonly used or recently proposed methods). The method used to calculate $^{\circ}\mathrm{C} \cdot \mathrm{d}$ for *E. saccharina* in the model is the one normally referred to either as the historical, simple or mean-minus-base method which calculates $^{\circ}\mathrm{C} \cdot \mathrm{d}$ accumulated on a single day simply as the difference between the arithmetic mean temperature and the threshold temperature of development. This method was chosen because the minimum temperatures experienced in the areas of interest to this study rarely fall below the required threshold temperatures for growth for each stage in the *E. saccharina* life cycle. Pruess (1983) argues that if this is the case, this method is similar to the more common sine wave method and loss in precision is minimal.

Let $T_{\mathrm{th}}^{\mathrm{e}}, T_{\mathrm{th}}^{\mathrm{sl}}, T_{\mathrm{th}}^{\mathrm{ll}}, T_{\mathrm{th}}^{\mathrm{p}}$ be the threshold temperature of development for the

stages egg, small larva, large larva and pupa, respectively. Let $T_{\text{ave}}(t)$ be the average temperature (in °C) on day t. The physiological age (in °C · d) of each cohort is then given by the recurrence equations

$$\begin{aligned}
DD_i^{\text{e}}(t+1) &= DD_i^{\text{e}}(t) + \max\left\{0, T_{\text{ave}}(t) - T_{\text{th}}^{\text{e}}\right\}, \quad i \in S_{\text{e}}(t) \\
DD_i^{\text{sl}}(t+1) &= DD_i^{\text{sl}}(t) + \max\left\{0, T_{\text{ave}}(t) - T_{\text{th}}^{\text{sl}}\right\}, \quad i \in S_{\text{sl}}(t) \\
DD_i^{\text{sl}}(t+1) &= DD_i^{\text{sl}}(t) + \max\left\{0, T_{\text{ave}}(t) - T_{\text{th}}^{\text{ll}}\right\}, \quad i \in S_{\text{sl}}(t) \\
DD_{i,j}^{\text{p}}(t+1) &= DD_{i,j}^{\text{p}}(t) + \max\left\{0, T_{\text{ave}}(t) - T_{\text{th}}^{\text{p}}\right\}, \quad j \in S_{\text{p}}^{i}(t)
\end{aligned}$$

with initial conditions

$$DD_t^{\text{e}}(t) = 0, \quad DD_t^{\text{sl}}(t) = 0, \quad DD_t^{\text{ll}}(t) = 0, \quad DD_{i,t}^{\text{p}}(t) = 0$$

Thermal constants and threshold temperatures of development for each stage in the *E. saccharina* lifecycle were calculated by Way (1995). The °C · d ranges ($DD_{\text{min}}^{\text{e}} - DD_{\text{max}}^{\text{e}}$) for the egg stage, ($DD_{\text{min}}^{\text{sl}} - DD_{\text{max}}^{\text{sl}}$) for the small larva stage, ($DD_{\text{min}}^{\text{ll}} - DD_{\text{max}}^{\text{ll}}$) for the large larva stage and ($DD_{\text{min}}^{\text{p}} - DD_{\text{max}}^{\text{p}}$) for the pupa stage were determined from the results of Way (1995) and are shown in Table 3.3 together with the corresponding thermal constants and threshold temperatures of development.

3.3.3 Maturation rates

It is well known that in biological populations, individuals mature at different rates. In *E. saccharina*, it has been noted that maturation from one stage to

Table 3.3: The threshold temperatures for development (T_{th}), thermal constants ($^{\circ}\text{C} \cdot \text{d}$) and the duration ($DD_{\min} - DD_{\max}$) of each stage in the *E. saccharina* lifecycle. Source: Way, 1995.

	T_{th} ($^{\circ}$C)	Thermal Constant ($^{\circ}\text{C} \cdot \text{d}$)	Duration ($^{\circ}\text{C} \cdot \text{d}$) $DD_{\min}$ - $DD_{\max}$
eggs	5.3	119	102 - 136
small larvae	10.2	219	185 - 253
large larvae	11.7	405	371 - 439
pupae	10.7	160	120 - 200

the next occurs over a period of a few days, depending on the stage that the population is in. Maturation begins when the physiological age of the cohort reaches $DD_{\min}$ for the stage that it is in. Data on the fractions that mature to the next stage per day is not yet available at SASRI. We therefore estimate the fractions of eggs that hatch from each of the egg cohort populations in existence on day t by

$$E_i^m(t) = \begin{cases} 0, & \text{if } DD_i^{\text{e}}(t) < DD_{\min}^{\text{e}} \\ \frac{DD_i^{\text{e}}(t) - DD_{\min}^{\text{e}}}{DD_{\max}^{\text{e}} - DD_{\min}^{\text{e}}}, & \text{if } DD_{\min}^{\text{e}} \leq DD_i^{\text{e}}(t) \leq DD_{\max}^{\text{e}} \\ 1, & \text{if } DD_i^{\text{e}}(t) > DD_{\max}^{\text{e}} \end{cases}$$

for each $i \in S_{\text{e}}(t)$. The above equation is based on the assumption that only a few of the individuals grow at a faster rate than the others, so initially, a small fraction will mature to the next stage and by the time the thermal constant is reached, at least 50% will have matured to the next stage and the slower ones follow. The fractions $SL_i^m(t), LL_i^m(t)$ and $P_{i,j}^m(t)$ are estimated using similar equations with the corresponding day-degree information used for each of the cohorts in existence on that day.

3.3.4 Oviposition rate

As mentioned in earlier sections, the daily oviposition rate of a moth depends on the size of the moth (determined by its "quality of life"), the temperature of the day and the number of days that the moth has lived.

The "quality of life" of each moth is a measure of the quality of its diet (i.e. the amount of nitrogen in the crop) during the time spent in the large larva stage. As CANEGRO does not give nitrogen content of the crop, we use the soil water deficit factor calculated by CANEGRO to give an indication of nitrogen content. According to Atkinson and Nuss (1989), the nitrogen content in sugarcane increases with a rise in crop water stress, thus the soil water deficit factor would be a good indicator of nitrogen content in the crop.

The soil water deficit factor calculated by CANEGRO is given as an index between 0 and 1, where 0 indicates that the crop is highly stressed and 1 indicates no stress. During the large larval stage, the model keeps track of the crop water stress index for each cohort. When members of cohort LLV_i mature to $PP_{i,t}(t)$, the sum of all the daily crop water stress indices experienced by the cohort up to day t divided by the number of days spent in the stage on day t is the "quality of life" index ($QLIND_{i,t}$) passed on to $PP_{i,t}(t)$. In other words, the "quality of life" index is the average of the daily stress index experienced during the large larva stage:

$$QLIND_{i,t} = \frac{1}{t-i} \sum_{j=t-i}^{t} \varsigma(j)$$

At a later time t' when members of $PP_{i,t}(t')$ become moths, the cohort $MTH_{i,t,t'}(t')$ is assigned the index $QLIND_{i,t}$.

We model the total number of eggs laid by female moths in cohort $MTH_{i,j,k}(t)$ on day t as follows

$$EGGLD_{i,j,k}(t) = 0.5 \times ELR(t-k) \times MTH_{i,j,k}(t) \times g_{\text{ind}}(QLIND_{i,j}) \times f_{\text{m}}(T_{\text{ave}}(t)) \tag{3.13}$$

where $ELR(n)$ is the egg laying rate n days after emerging, g_{ind} is the "quality of life" index multiplier function, f_{m} is the temperature multiplier function and 0.5 represents the *E. saccharina* sex ratio. Thus the oviposition rate for moth cohort $MTH_{i,j,k}(t)$ is given by

$$O_{i,j,k}(t) = 0.5 \times ELR(t-k) \times g_{\text{ind}}(QLIND_{i,j}) \times f_{\text{m}}(T_{\text{ave}}(t)) \tag{3.14}$$

Because moths that have had a "good quality of life" produce more viable eggs, the function g_{ind} is a function of the shape shown in Figure 3.4.

3.4 Testing the model

Before calibrating the model, it is necessary to "verify" the model. By verification, we mean checking whether the computer program is a correct representation of the logic used in structuring the model.

This is achieved by checking model response to temperature and crop water stress and to check the impact of the crop resistance rating on larvae survival.

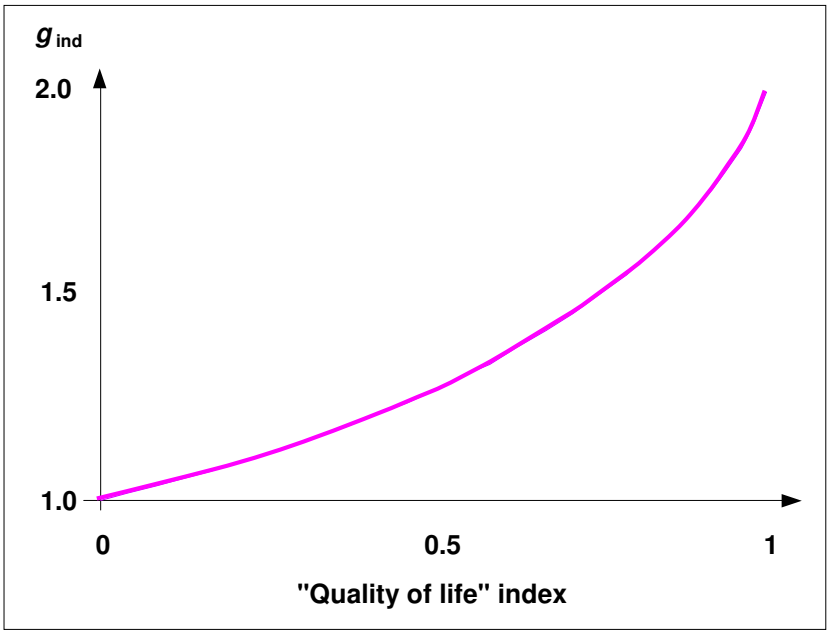

Figure 3.4: The shape of the "quality of life" index multiplier function g_{ind}.

We expect that as temperatures increase, maturation from one stage to the next will occur sooner, mortality rates will increase and moth fecundity rates will rise. An increase in crop water stress should indicate higher infestation rates and higher moth fecundity rates. Crop resistance ratings above 5 should indicate higher infestation rates while those below 5 should indicate low infestation rates.

3.4.1 Response to temperature

To test model response to temperature, daily crop water stress index was kept fixed at intermediate, crop variety was set to 5 and simulations were run with temperatures held constant at 15°C, 20°C, 25°C and 30°C, respectively. The simulations were each kicked off with one cohort of 300 eggs and ran over a period of 200 days. The results were then checked against laboratory results from Way (1995). Development times (in days) to complete the various stages in the *E. saccharina* lifecycle at constant temperatures of 15°C, 20°C, 25°C and 30°C (as found by Way (1995)) are shown in Table 3.4.

Table 3.4: Average total development time for immature *E. saccharina* life stages reared at various constant temperatures. Source: Way (1995).

Temperature	Average development period (days)			
(°C)	Egg	Small Larva	Large Larva	Pupa
15	13	85	97	38
20	9	36	51	20
25	6	18	30	10
30	5	13	23	8

As can be seen from Figure 3.5, the simulation results closely agree with the data shown in Table 3.4. By looking at the timing of the peaks, it can be seen that at higher temperatures, the peaks occur sooner indicating that development is faster as suggested by the rates in Table 3.4. The initial peaks in numbers of small larvae, large larvae, pupae and moths in the simulation results also show the relationship between temperature and mortality rates

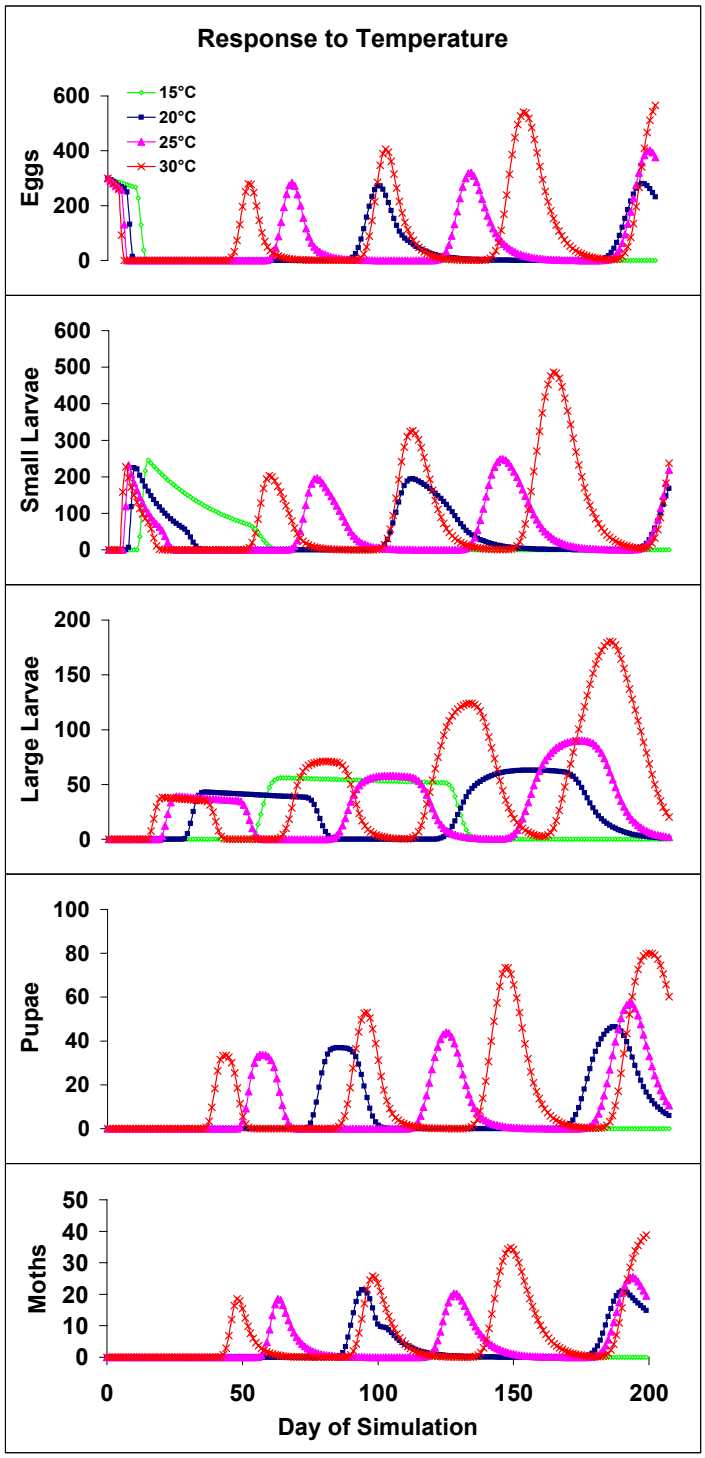

Figure 3.5: Simulation results showing model response to temperature. All graphs share the horizontal axis given in the graph for moths.

given in Table 3.2. The model, therefore, responds as expected when tested for its response to various temperature conditions.

3.4.2 Response to crop water stress

To test model response to crop water stress, simulations were run with temperature held constant at 25°C, crop resistance rating at intermediate. Crop water stress index was varied to test model response to low crop water stress, intermediate crop water stress and high crop water stress. The results of these simulations are shown in Figure 3.6. The results again show the model to respond as expected under varying crop water stress.

3.4.3 Response to crop resistance rating

Model response to crop resistance rating was tested by setting daily temperature constant at 25°C, daily crop water stress index constant at intermediate. Simulations were run to test crops of high susceptibility (rating 9), intermediate susceptibility (rating 5) and low susceptibility (rating 2). The results of the simulations are shown in Figure 3.7. In this test, it is again noted that the model responds as expected when run for crops of varying susceptibility to *E. saccharina* attack.

Now that the model has been verified, the next step is to calibrate it.

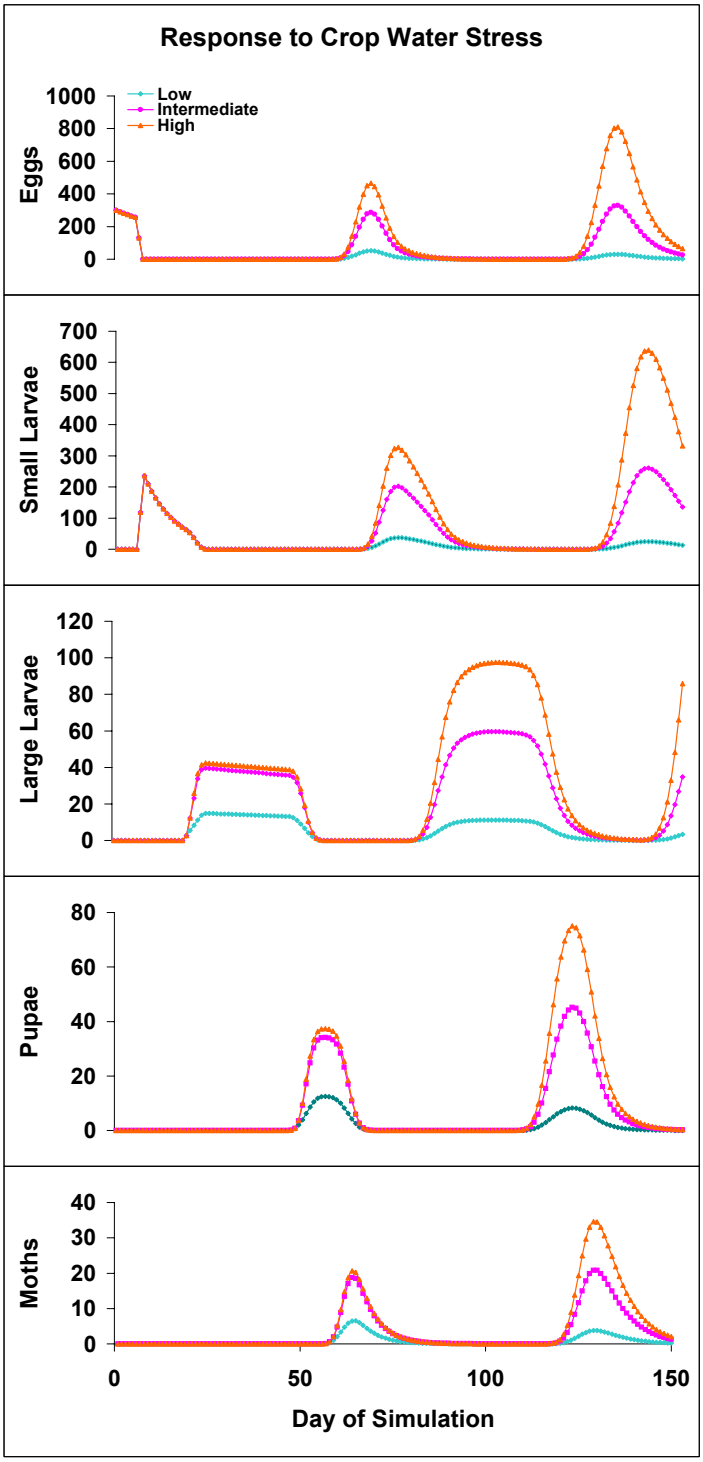

Figure 3.6: Simulation results showing model response to crop water stress. All graphs share the horizontal axis given in the graph for moths.

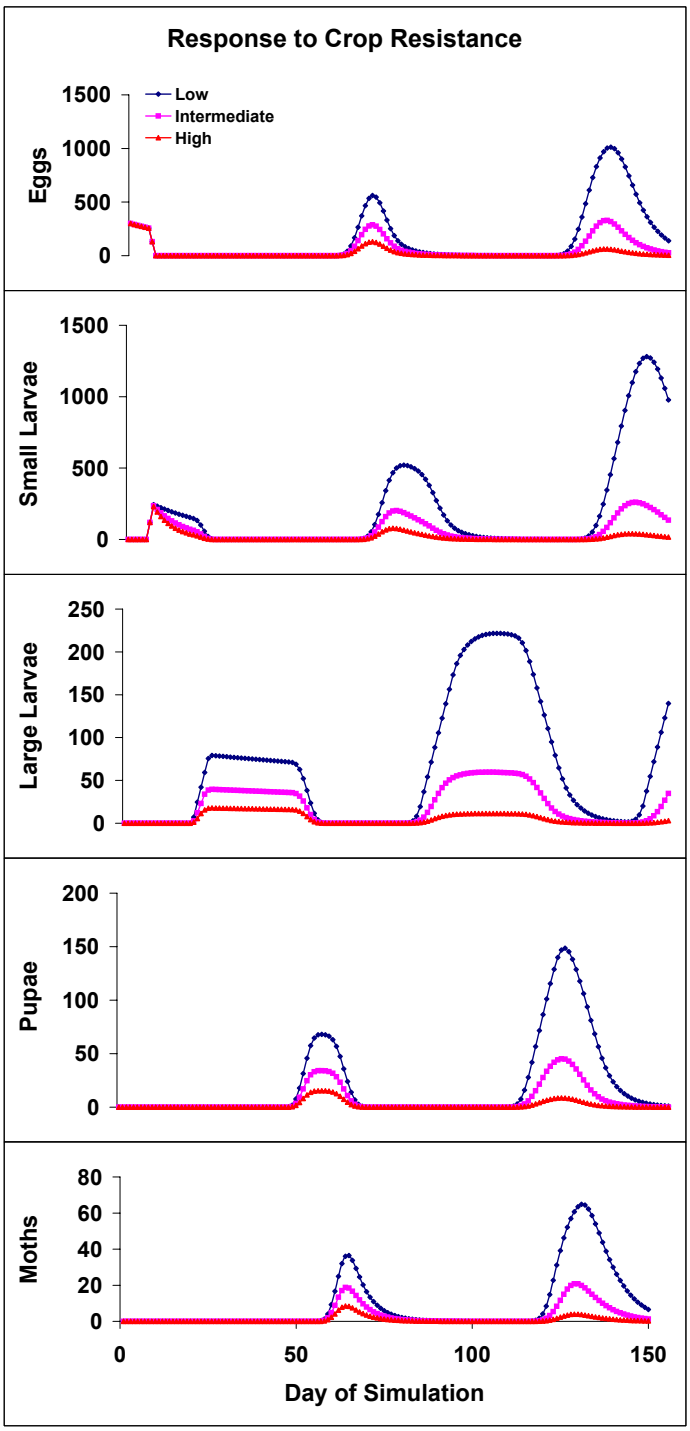

Figure 3.7: Simulation results showing model response to crop varietal resistance to *E. saccharina* attack. All graphs share the horizontal axis given in the graph for moths.

3.5 Model calibration

According to Rykiel Jr. (1996), model "calibration is the estimation and adjustment of model parameters and constants to improve the agreement between model output and a data set".

In the model developed in this study, unknowns include the number of eggs used in the initialization of the model (EGG_{ini}), effect of crop water stress on the mortality of small larvae and large larvae, and the combined effect of crop water stress and temperature on moth oviposition rates. The threshold temperature of development for large larvae may need to be adjusted, as temperature experienced inside the sugarcane stalk may not be the same as the air temperature (Way, pers. comm.).

In order to calibrate the model, field data sets were selected for SASRI Mtunzini field station field 013 (variety NCo376; *E. saccharina* resistance rating 7 – moderately susceptible to attack by *E. saccharina*. These data sets were selected mainly because of the field data sets available, the most commonly grown variety in the industry was NCo376). The data gives a record of monthly field surveys of counts of *E. saccharina* larvae and pupa (in e/100s) taken over the four year period between August, 1988 and August, 1991. Crop cycles for this period were annual, giving a total of four annual counts of monthly *E. saccharina* infestation levels for this field. The model was run concurrently with the CANEGRO model for each of the four cycles and model

output of *E. saccharina* larvae (e/100s) were compared with field data. Various *E. saccharina* parameters in the model were adjusted until a satisfactory fit with actual field data was achieved.

Since the model is not designed to distinguish between trashed or burnt fields and assumes an *E. saccharina* free field in its initialization, the field data sets used were for burnt field blocks because field burning reduces chances of *E. saccharina* remaining in the field after harvest.

Some problems were encountered in calibrating the model stemming from the fact that field data taken from various blocks within the same field varied widely. The average numbers of large larvae plus pupae recorded from the different blocks within the field were therefore used in calibrating the model.

Another difficulty arose when determining EGG_{ini}. The value of EGG_{ini} can not be assumed to be constant because moth numbers in the field have shown seasonal as well as annual fluctuations (Carnegie and Leslie, 1990). Figure 3.8 shows the monthly trend of *E. saccharina* moth populations caught in traps placed in sugarcane fields over a ten year period.

In order to accommodate the moth trends shown in Carnegie and Leslie (1990), it was decided that the number of eggs used in initializing the model, EGG_{ini}, should be a reflection of this trend. The number of eggs used in model initialization after model calibration is given in Table 3.5.

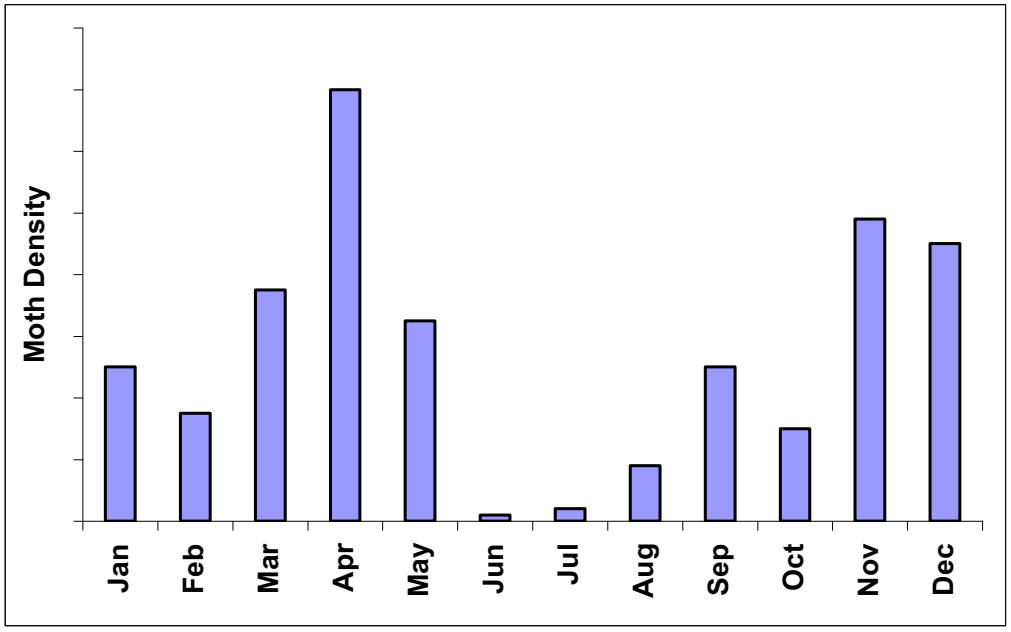

Figure 3.8: The trend of *E. saccharina* moth populations trapped in light traps in sugarcane on a monthly basis over a ten year period. Source: Carnegie and Leslie (1990).

Table 3.5: The number of *E. saccharina* eggs used in initializing the model, EGG_{ini}, for each month of the simulation based on the *E. saccharina* moth trends of Figure 3.8 and model calibration.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max. eggs	7	4	10	19	8	1	1	3	7	5	15	13

The other parameters used in the model after calibration are given in Table 3.6 and Table 3.7.

Table 3.6: Threshold temperatures for development and mortality rates used in the model after calibration.

	Egg	Small Larva	Large Larva	Pupa
Threshold temperature (°C)	5.3	10.2	11.2	10.7
Mortality rate (/day)	0.05	0.166	0.009	0.007

Table 3.7: Number of viable eggs laid per female *E. saccharina* moth on each day after emerging (based on model calibration).

Moth age (days)	1	2	3	4	5
Number of eggs laid (per female moth)	3	5	7	5	3

The fit of the calibrated model with the data set used in model calibration is shown in Figure 3.9. The fit is quite good for the first and fourth crop cycles. It would be very difficult to always get a close fit with field data because (1) as mentioned earlier, the number of eggs used in the initialization is generated randomly, (2) the fields were occasionally pre-trashed in order to minimize *E. saccharina* incidence, in which case the model may show higher

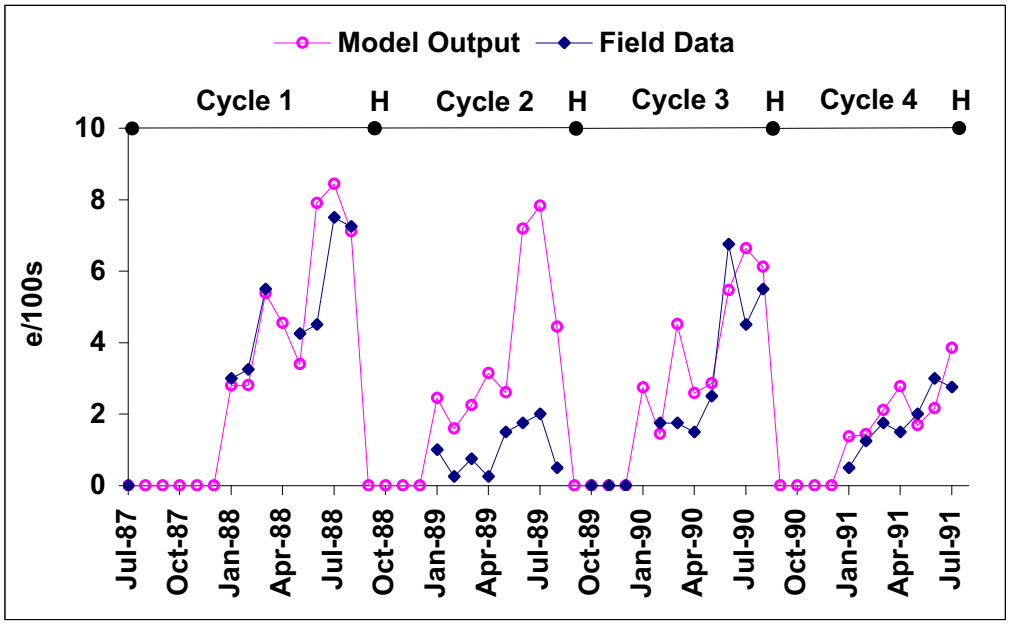

Figure 3.9: Calibrated model output fit with the data set used in calibrating the model. H indicates the date of harvest for each crop cycle.

larvae populations than the field recordings and (3) the available field data were obtained by taking 100 stalks from the field at random and dissecting them to obtain the field reading of e/100s. While the latter has been used as an indicator of *E. saccharina* infestation levels on sugarcane farms, the readings may be influenced by the area of the field where the stalk samples were obtained. *E. saccharina* counts have been shown to vary from block to block within the same field (see, e.g., Figure 3.10).

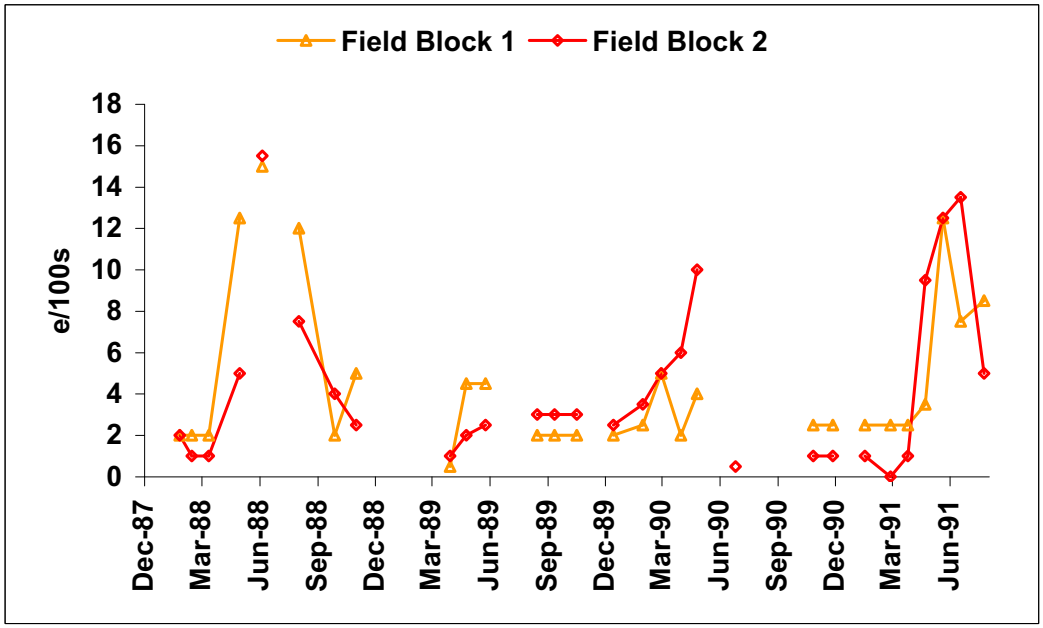

Figure 3.10: Field data for a field at SASRI La Mercy field station, KwaZulu-Natal showing the differences in readings between two blocks within the same field.

3.6 Model validation

There are varying views in the literature on model validation. Some authors consider validation impossible (e.g., Starfield and Bleloch, 1986), others suggest it is possible (e.g., Law and Kelton, 1991) and a further group believes that models can only be invalidated (e.g., Holling, 1978).

The following guideline on validation is offered by Rykiel, Jr. (1996): "validation is better understood as a process that results in an explicit statement

about the behaviour of a model." It needs to be shown that the model possesses a satisfactory range of accuracy, within its domain of applicability, consistent with the intended application of the model.

The *E. saccharina* model developed here is designed to simulate populations in the various stages of development in the *E. saccharina* life cycle under various temperature regimes and crop conditions. To initialize the model, it is assumed that fields adjacent to the areas where the model is to be applied have *E. saccharina* present and some moths from these fields will lay eggs on sugarcane planted in these areas. As argued in the section on calibrating the model, because of this, there will always be some variation between model output and field data.

In order to test the validity of the model, data sets from SASRI similar to the one used when calibrating the model were used. The results of model simulations conducted concurrently with CANEGRO for crop cycles that match these data sets, compared with the actual field data are shown in Figure 3.11 and Figure 3.12.

From the results shown in Figure 3.11, we see that the model gives a reasonably good fit to the field data corresponding to the second and third crop cycles, bearing in mind the variability in *E. saccharina* counts from one block to the next within one field. A similar close fit is achieved for the third crop cycle in Figure 3.12.

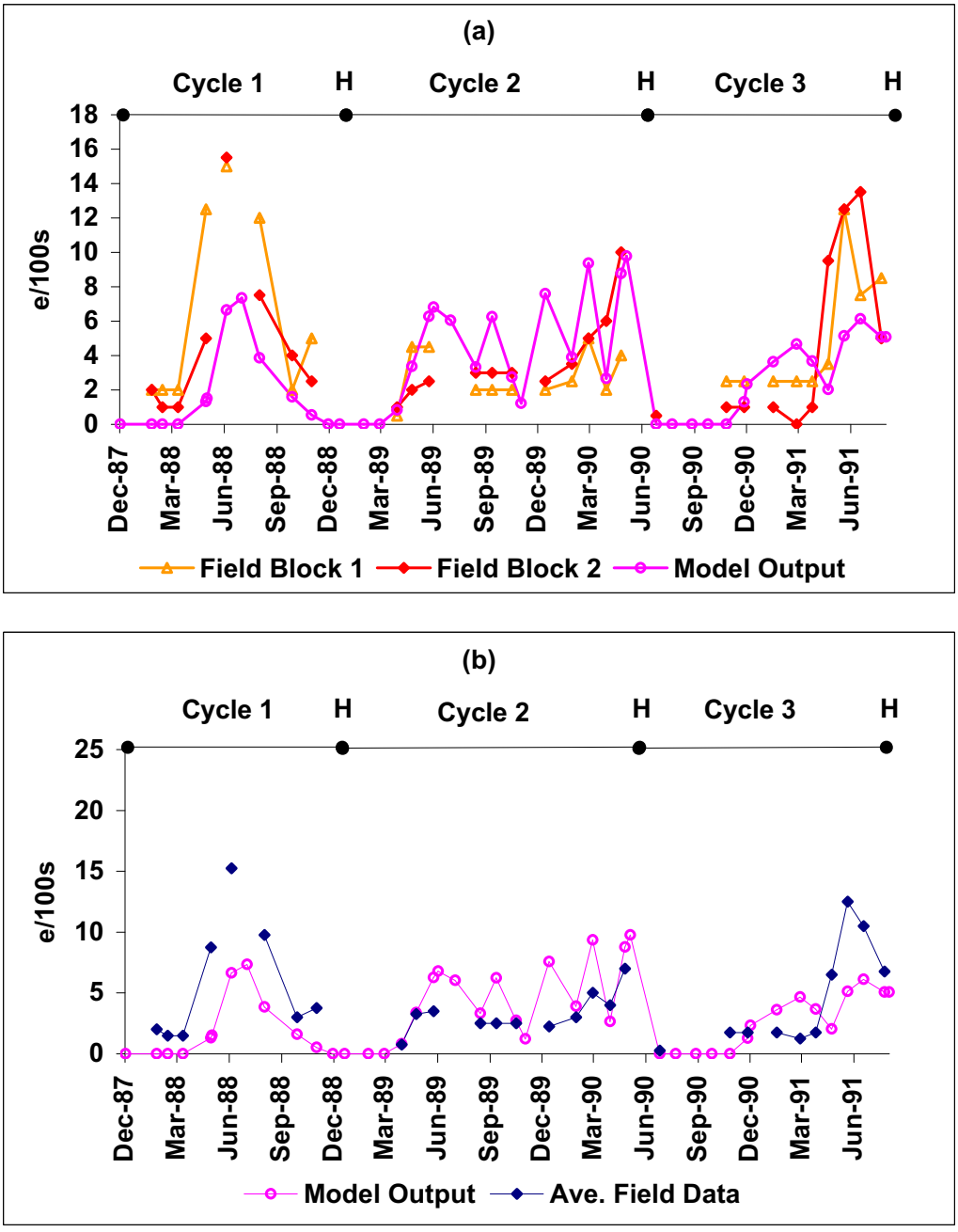

Figure 3.11: Model output compared with actual field data for a field at SASRI LaMercy field station, KwaZulu-Natal. In (a), model output is compared with two data sets taken from different blocks within the field while in (b), model output is compared with the average of the two data sets.

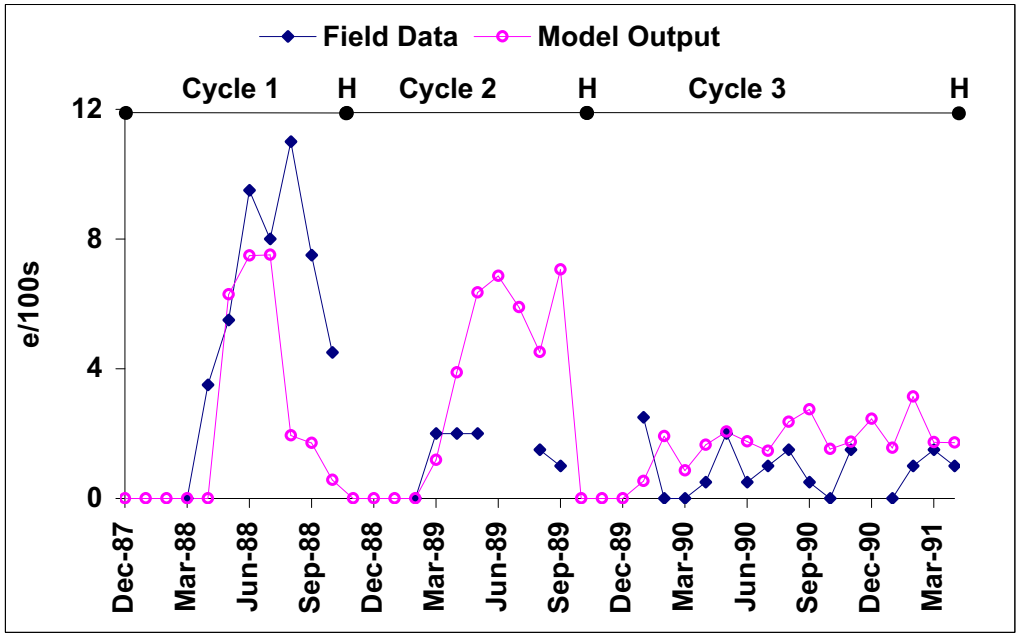

Figure 3.12: Model output compared with actual field data for a field at SASRI LaMercy field station, KwaZulu-Natal.

In fact the above conclusions were confirmed when independent two-sample t-tests were carried out where the two samples are the field data and model output. For example, in Figure 3.11 it was found that when comparing Field Block 1 data with model output, a t-value of -0.39 for 86 degrees of freedom was found. This is a small t-value. This was also confirmed by a p-value of 0.696 (> 0.05). For Field Block 2, we found a t-value of -0.48 and a p-value of 0.633. For the data shown in Figure 3.12, a t-value of -0.82 and a p-value of 0.416. This statistical analysis confirms that the model output is not significantly different from the field data.

A question that comes to mind is: how does the model behave when the initial

E. saccharina population is known? Field data whereby initial *E. saccharina* populations are known are not currently available. In order to answer the above question an alternative source of data was sought. Data sets available at SASRI which could aid in finding an answer were found to be those of routine potted sugarcane screening trials, conducted between 1996 and 1998, to evaluate the susceptibility of sugarcane varieties to *E. saccharina* . In these trials, water stressed potted sugarcane plants were inoculated with a known number of eggs that were in the 'black head' stage of development and which hatched within 24 hours. Infestations were allowed to develop over a period required to accumulate $500°\text{C} \cdot \text{d}$ (with a developmental temperature threshold of 10°C), by which time the majority of individuals had developed to the large larval stage or, less commonly the pupal stage. At this stage, the pots were harvested and data was recorded. The data recorded from each stalk included stalk length, length of borer tunnels and number of large larvae, pupae and pupal cases. The latter were rarely found.

The above data sets were used to check the validity of the model as follows. From each field trial data set, the average number of eggs used in the inoculation of each pot and the average number of large larvae and pupae that were recovered were calculated when the pot plants were harvested. Crop water stress index was kept at high (0.9) and daily temperature data corresponding to the period under consideration was used. The model was initialized with a population of eggs equivalent to the number of eggs used in the inoculation of the potted sugarcane plant trials and run for an equivalent of $500°\text{C} \cdot \text{d}$ (at a temperature threshold of 10°C). At the end of the model run, the total

number of large larvae plus pupae calculated by the model was compared against the data collected from the potted plant trials. This comparison is shown in Table 3.8 for various crop varieties with *E. saccharina* resistance rating indices ranging from 2 (high resistance) to 9 (low resistance).

Table 3.8: Comparison between model output and data sets for crop varieties of varying susceptibility to *E. saccharina* ($500°C \cdot d$ after eggs hatch).

Crop Variety (ρ)	Number of Data Sets	Percent Match	Ave. Percent Diff. From Data Sets (non-matches only)	Standard Deviation
N21(2)	15	66.7	13.7	50.2
N12 (3)	8	37.5	-19.3	22.8
N40 (5)	1	0	-14.3	-
NCo376 (7)	15	73.3	-8.5	21.9
N16 (8)	4	75.0	16.7	-
N11 (9)	15	73.3	-12.8	15.8
N26 (9)	2	50.0	-15.1	1.4
Overall	60	65	-6.1	30.1

The data sets referred to in Table 3.8 were grouped as follows. Data recorded from pots containing sugarcane plants of the same crop variety that were inoculated with eggs on the same day were grouped into one data set. Thus, each data set can contain information taken from between four and 24 pots each containing five stalks of sugarcane. To kick off the model, the average of the number of eggs used to inoculate each pot in that data set was used. The procedure to determine a match between model output and a data set is as follows. The average of the numbers of large larvae plus pupae (or empty pupae) recovered in each pot at the end of the trial together with the standard deviation were used to determine a range of large larvae plus pupae that can

be expected from the average number of eggs used in the inoculation. A 99% confidence level was used to determine the required range (i.e., 99% certainty was required that the mean would be within the range of values used). Model output was then considered to match the data set if it produced large larvae plus pupae that fell within this range. The percent difference shown in the table was determined by calculating how far from being within the range the model output was, a negative value indicating the percent shortfall from the lower end of the range and a positive value indicating how far the upper end of the range was exceeded.

Based on the results shown in Table 3.8, the following statements on the performance of the model can be made: (1) the model has good predictive capabilities of larval trends for crop varieties N21 (correct two out of three times); NCo376, N16 and N11 (correct three out of four times), (2) when not correct, the percent deviation is, on average, low and (3) overall, the model is correct 65% of the time with the tendency to underestimate larval infestation levels. It should be stressed here that the above statements hold when the initial egg populations are known.

When the model is run without the knowledge of the initial population distribution, we make the the following statement based on the fit of the model with field data shown in Figures 3.11 and 3.12: while the model will not always fit field data exactly, the model is able to pick up the timing of the various peaks in larval numbers and because control measures should be timed based on these peaks, the model can be useful as an indicator for the

timing of control measures. Future trends in crop damage can also be studied using the model because as demonstrated in Table 3.8, once a starting point has been identified, the predictive capabilities of the model are quite good.

From here on, any simulations performed will be based on a field of area one hectare containing 130 000 sugarcane stalks (see Hearne et al., 1994) of variety (unless otherwise stated) NCo376. NCo376 was chosen because the field data used when calibrating the model was from a field containing NCo376 and the model showed good performance for this variety (see Table 3.8).

Chapter 4

Biological control model

4.1 Introduction

Classical biological control is the purposeful introduction of natural parasitoids of a pest from the region of the pest's origin, specifically for the purpose of suppressing the abundance of the pest population to levels at which it no longer causes economic damage in the region that the pest has moved to. A pure classical biological control approach against *E. saccharina* cannot be considered in South Africa (Conlong, 1994a; Conlong, 1994b) because it (*E. saccharina*) is African in origin (Atkinson, 1980) and has not moved into a new region. Over the past twenty years, SASRI has been investigating various indigenous and exotic parasitoids for their effect on controlling *E. saccharina* infestations in sugarcane and has adopted two biological control

approaches; a 'new association' approach and a modified classical biological control approach (Conlong, 1997).

The 'new association' approach is a method which tests parasitoids of stem borers from other parts of the world against *E. saccharina* life stages. Thus far, the method has shown no significant success in tests conducted by SASRI (Conlong, 1994b).

The other method uses classical biological control principles. Conlong (1990) argued that because *E. saccharina* is indigenous to wetland sedges and grasses and has only recently colonized graminaceous crops, it escaped its natural enemies in the indigenous plants. Thus, classical biological control principles could be applied because this situation was analogous to an insect moving from its indigenous home country, where it lived in balance with its natural enemies, to a new country where those natural enemies did not occur. The 'modified' classical biological control approach has yielded some positive results as some parasitoids have been identified for possible use in the control of *E. saccharina* (Conlong, 1997).

One parasitoid which has shown some promise for use as a biological control agent for *E. saccharina* is *Sturmiopsis parasitica* Curran (Diptera: Tachinidae) which was recovered from *E. saccharina* in maize in Benin, West Africa in 1995/1996 (Martin, 2002). *S. parasitica* is a larval parasitoid which attacks *E. saccharina* larvae in instars V and VI (Martin, 2002). There are three main stages in the life cycle of *S. parasitica*. These are the maggot,

pupa and adult stages. Adult female *S. parasitica* deposit live maggots at the entrance to the boring hole left by the stalk borer (normally indicated by frass on the stalk in the case of *E. saccharina*). The maggots then crawl into the hole to find the host larva and parasitize it (Martin, 2002).

In this chapter, a host-parasitoid model of the interactions between *E. saccharina* and *S. parasitica*is developed by building onto the model developed in Chapter 3. This is done in order to test various management strategies so as to aid and enhance the research being currently done on the viability of *S. parasitica* as a possible biological control agent for *E. saccharina* .

4.2 Formulation of the host-parasitoid model

In order to study the interactions between the pest *E. saccharina* and the parasitoid *S. parasitica*, a simulation model based on the lifecycle of *S. parasitica* is developed. The *E. saccharina* model is then modified in order to achieve a dynamic interaction with the parasitoid model. This dynamic interaction is shown in Figure 4.1.

In what follows, the parasitoid sector of the host-parasitoid model is first described followed by the description of the modified *E. saccharina* model.

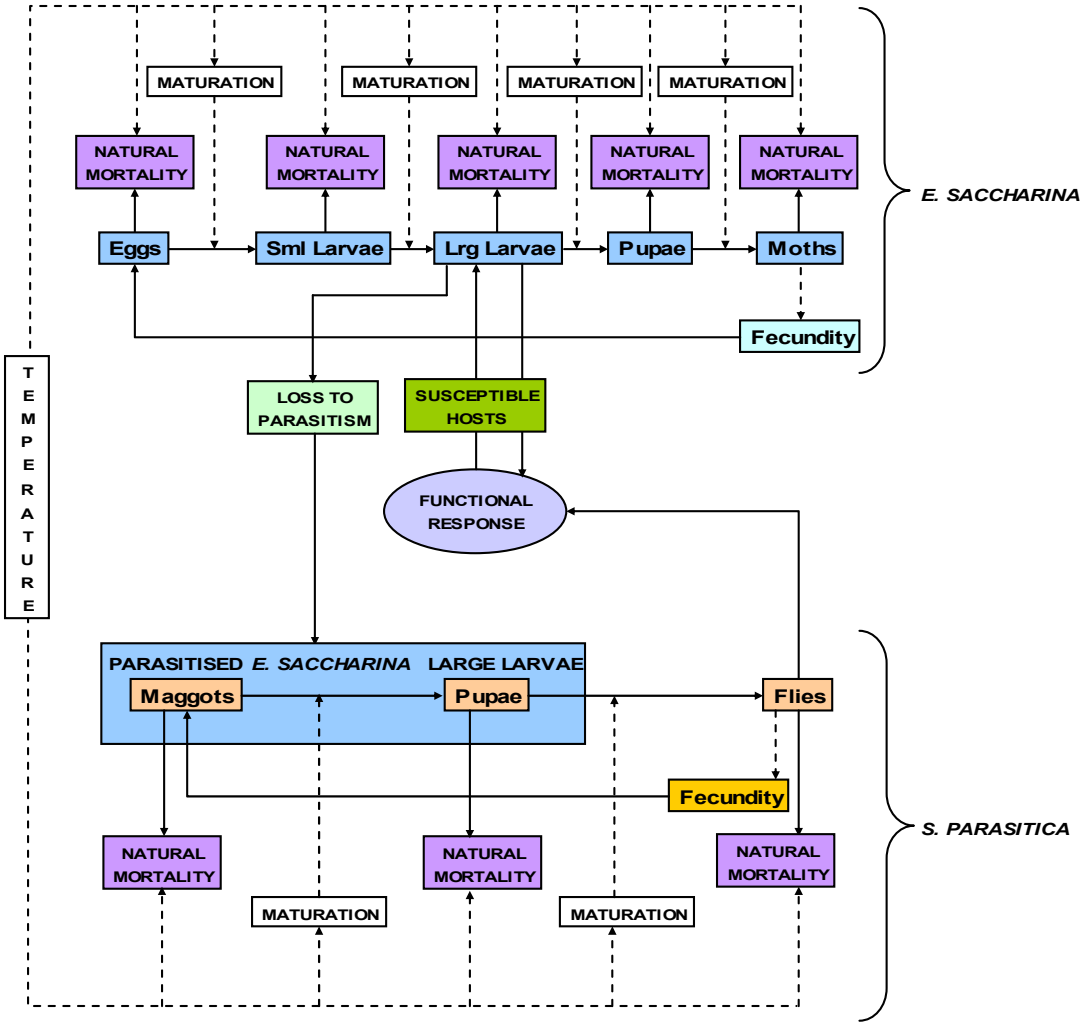

Figure 4.1: Interaction between the *E. saccharina* model and the *S. parasitica* model.

4.2.1 The *S. parasitica* sector

To incorporate the effects of temperature on the dynamics of *S. parasitica*, a cohort based model not very different in structure from the *E. saccharina* model was used. Let $MGT_i(t), SPP_i(t)$ and $FLY_i(t)$ represent the number on day t of members of the cohort that began, respectively, the maggot, pupa and fly stages in the *S. parasitica* life cycle on day i. ($SPP_i(t)$ is used in order to distinguish *S. parasitica* pupal cohorts from *E. saccharina* pupal cohorts, which are given by $PP_{i,j}(t)$. Also note that the maggot stage was not divided into two groups as was done for the larva stage in the *E. saccharina* model. The structure of the *S. parasitica* model is thus slightly less complex.)

Let $DD_i^{\text{mg}}(t), DD_i^{\text{spp}}(t)$ represent, respectively, the physiological age (in $^\circ\text{C} \cdot$ d) of the corresponding maggot and pupal cohort. $MGT_i^d(t)$, $SPP_i^d(t)$ and $FLY_i^d(t)$ denote the fraction of members of the corresponding maggot, pupa and fly cohort respectively that die during day t. Similarly, $MGT_i^m(t)$ and $SPP_i^m(t)$ denote the fraction of members of the corresponding maggot and pupal cohort respectively that mature to the next stage. The minimum physiological age and maximum physiological age required to complete each stage are represented respectively by $DD_{\text{min}}^{\text{mg}}, DD_{\text{max}}^{\text{mg}}$ for the maggot stage and $DD_{\text{min}}^{\text{spp}}, DD_{\text{max}}^{\text{spp}}$ for the pupal stage. Table 4.1 gives the stage specific mortality rates, the threshold temperatures (in $^\circ$C) for development and the duration of each stage (in $^\circ\text{C} \cdot$ d) in the life cycle of *S. parasitica*.

For indexing purposes, we define the following sets similar to those used in

Table 4.1: The stage specific daily mortality rates, threshold temperatures for development and stage durations for *S. parasitica*. Source: Martin (2002) and SASRI.

Stage	Mortality rate at 25°C (/day)	Threshold temperature (°C)	Duration (°C · d) $DD_{\min} - DD_{\max}$
Maggot	0.181	12.8	225.4 – 236.0
Pupa	0.013	17.4	152.7 – 163.1
Fly	0.070	–	–

the *E. saccharina* model

$$\begin{aligned} S_{\text{mg}}(t) &= \left\{t, t-1, t-2, \ldots, t-\tau_{\text{mg}} : DD^{\text{mg}}_{\tau_{\text{mg}}}(t) \leq DD^{\text{mg}}_{\max} < DD^{\text{mg}}_{\tau_{\text{mg}}-1}(t)\right\}, \\ S_{\text{spp}}(t) &= \left\{t, t-1, t-2, \ldots, t-\tau_{\text{spp}} : DD^{\text{spp}}_{\tau_{\text{spp}}}(t) \leq DD^{\text{spp}}_{\max} < DD^{\text{spp}}_{\tau_{\text{spp}}-1}(t)\right\}, \\ S_{\text{fly}}(t) &= \left\{t, t-1, t-2, \ldots, t-\tau_{\text{fly}} : \tau_{\text{fly}} = FLYDYS_{\max}\right\}, \end{aligned}$$

where $FLYDYS_{\max}$ is the maximum number of days a *S. parasitica* fly can live. These sets ensure that only cohorts that are in existence on day t are considered. For example, the eldest maggot cohort on day t is the one that began on day τ_{mg}. Its physiological age is $DD^{\text{mg}}_{\tau_{\text{mg}}}(t)$ and its chronological age is $t - \tau_{\text{mg}}$. The cohort of chronological age $t - \tau_{\text{mg}} + 1$ that began the day before that will have matured to the pupal stage.

With the above notation, the populations of all cohorts in the various stages of development in the *S. parasitica* life cycle are given by the following system of equations

$$\begin{aligned} MGT_i(t+1) &= MGT_i(t) \times \left(1 - MGT^d_i(t) - MGT^m_i(t)\right), \quad i \in S_{\text{mg}}(t) \\ SPP_i(t+1) &= SPP_i(t) \times \left(1 - SPP^d_i(t) - SPP^m_i(t)\right), \quad i \in S_{\text{spp}}(t) \\ FLY_i(t+1) &= FLY_i(t) \times \left(1 - FLY^d_i(t)\right), \quad i \in S_{\text{fly}}(t) \end{aligned} \tag{4.1}$$

The initial conditions of system (4.1) are given by equations (4.2) through to (4.4) below.

$$MGT_t(t) = \sum_{i \in S_{\text{ll}(t)}} n_i(t) \times p_{i,t}(t) \tag{4.2}$$

$$SPP_t(t) = \sum_{i \in S_{\text{mg}(t)}} MGT_i(t) \times MGT_i^m(t) \tag{4.3}$$

$$FLY_t(t) = \sum_{i \in S_{\text{spp}(t)}} SPP_i(t) \times SPP_i^m(t) \tag{4.4}$$

where $n_i(t)$ in equation (4.2) is the rate at which each *E. saccharina* larva parasitized is converted into a female *S. parasitica* maggot (maggots/larva) and $p_{i,t}(t)$ is the total number of members of the cohort $LLV_i(t)$ of *E. saccharina* large larvae that have been parasitized on day t. Equation (4.2) indicates that parasitism is distributed over all larval cohorts in existence. Note that $p_{i,j}(t)$ describes the population on day t of all the larvae in the cohort $LLV_i(t)$ that were successfully parasitized by maggots on day j. The equations governing all $p_{i,j}(t)$ are discussed in a section that follows.

Parasitoid mortality rates

The mortality rates for each stage in the *S. parasitica* life cycle are modeled by equations similar to those given in equations (3.8) to (3.12), which describe

the mortality rates for *E. saccharina* stages, as follows:

$$MGT_i^d(t) = d_{\text{mg}} \times f_{\text{mg}}(T(t)), \tag{4.5}$$

$$SPP_i^d(t) = d_{\text{spp}} \times f_{\text{spp}}(T(t)) \tag{4.6}$$

$$FLY_i^d(t) = d_{\text{fly}} \times f_{\text{fly}}(T(t)) \tag{4.7}$$

where $d_{\text{mg}}, d_{\text{spp}}$ and d_{fly} are the specific daily mortality rates at a temperature of 25°C and the functions $f_{\text{mg}}(T(t))$, f_{spp} and f_{fly} are multiplier functions used to represent the effect of temperature on these rates.

The maggot mortality rate given by Equation (4.5) does not include the dynamics of the parasitized larvae because it is assumed that once maggots have found a host they will continue to feed on it even after it has died. The same applies to larvae that metamorphose to pupa before maggots pupate (Walton, pers. comm., has observed *S. parasitica* flies emerging from *E. saccharina* pupae).

Physiological age and maturation rates

The number of degree-days accumulated by the parasitoid is calculated by equations similar to those used in the *E. saccharina* model. Let $T_{\text{th}}^{\text{mg}}$ and $T_{\text{th}}^{\text{spp}}$ be the threshold temperatures for development for the maggot and pupa stages respectively. The physiological age of each cohort in the immature

stages of the *S. parasitica* lifecycle is given by

$$\begin{aligned} DD_i^{\text{mg}}(t+1) &= DD_i^{\text{mg}}(t) + \max\left\{0, T_{\text{ave}}(t) - T_{\text{th}}^{\text{mg}}\right\},\ i \in S_{\text{mg}}(t) \\ DD_i^{\text{spp}}(t+1) &= DD_i^{\text{spp}}(t) + \max\left\{0, T_{\text{ave}}(t) - T_{\text{th}}^{\text{spp}}\right\},\ i \in S_{\text{spp}}(t) \end{aligned}$$

Once the physiological age of the cohort reaches the minimum number of degree days required to complete the stage of development it is in, members begin metamorphosis to the next stage. The fraction that mature to the next stage on day t is approximated by the following equations:

$$MGT_i^m(t) = \begin{cases} 0, & \text{if } DD_i^{\text{mg}}(t) < DD_{\text{min}}^{\text{mg}} \\ \frac{DD_i^{\text{mg}}(t) - DD_{\text{min}}^{\text{mg}}}{DD_{\text{max}}^{\text{mg}} - DD_{\text{min}}^{\text{mg}}}, & \text{if } DD_{\text{min}}^{\text{mg}} \le DD_i^{\text{mg}}(t) \le DD_{\text{max}}^{\text{mg}} \\ 1, & \text{if } DD_i^{\text{mg}}(t) > DD_{\text{max}}^{\text{mg}} \end{cases},$$

for each $i \in S_{\text{mg}}(t)$, and

$$SPP_i^m(t) = \begin{cases} 0, & \text{if } DD_i^{\text{spp}}(t) < DD_{\text{min}}^{\text{spp}} \\ \frac{DD_i^{\text{spp}}(t) - DD_{\text{min}}^{\text{spp}}}{DD_{\text{max}}^{\text{spp}} - DD_{\text{min}}^{\text{spp}}}, & \text{if } DD_{\text{min}}^{\text{spp}} \le DD_i^{\text{spp}}(t) \le DD_{\text{max}}^{\text{spp}} \\ 1, & \text{if } DD_i^{\text{spp}}(t) > DD_{\text{max}}^{\text{spp}} \end{cases},$$

for each $i \in S_{\text{spp}}(t)$.

Parasitism

The number of members of each *E. saccharina* large larva cohort that are attacked by *S. parasitica* maggots on day t is described by:

$$p_{i,t}(t) = \frac{LLV_i(t)}{TLLV(t)} \times TMGT(t) \times SPR \times f_L(\delta(TLLV(t))) \times f_M(\delta(TMGT(t))) \tag{4.8}$$

where

$$\begin{aligned} TLLV(t) &= \sum_{i \in S_{\text{ll}}(t)} LLV_i(t), \\ TMGT(t) &= \sum_{i \in S_{\text{fly}}(t)} FLY_i(t) \times O(FLY_i(t)), \end{aligned}$$

are, respectively, the total number of *E. saccharina* large larvae and the total number of *S. parasitica* maggots laid by flies on day t. The functions f_L and f_M are density dependent multiplier functions to represent the effect of larval density (denoted by $\delta(TLLV(t))$) and maggot density (denoted by $\delta(MGT(t))$), respectively, on the specific parasitism rate SPR, which is the number of *E. saccharina* larvae parasitized per *S. parasitica* maggot per day (units: large larvae/maggot/day).

The oviposition rate $O(FLY_i(t))$ of the fly cohort $FLY_i(t)$ is determined by the number of days the fly has lived (for $FLY_i(t)$, the chronological age is $(t - i)$). *S. parasitica* flies normally start laying maggots from day 8 after emerging (Martin, 2002). The number of maggots laid per fly on various days after emerging is given in Table 4.2.

Table 4.2: The number of maggots laid by each *S. parasitica* fly at various days after emerging. Before day 8 and after day 14, no maggots are laid.

FLYAGE (days)	8	9	10	11	12	13	14
Maggots laid (/fly)	50	50	50	100	100	150	150

The first term in equation (4.8) is used to ensure that the number of members of the cohort exposed to parasitism is determined according to the size of the

cohort population relative to the total number of large larvae on that day.

The density dependent functions f_L and f_M were chosen intuitively based on observations that parasitism is low when host densities are low, increasing slowly at first as larval density increases and eventually taking a decelerating rise to an upper asymptote (i.e. f_L is sigmoidal in shape representing a Holling (1959) type III functional response (see Figure 4.2 (a))). As parasitoid density increases to high levels, a decline in the specific parasitism rate (because of competition) is observed. The decline in specific parasitism rate is represented by the function f_M whose shape follows that shown in Figure 4.2 (b). Functions of the shapes of f_L and f_M are discussed further in Appendix A.1 and Appendix A.2 respectively.

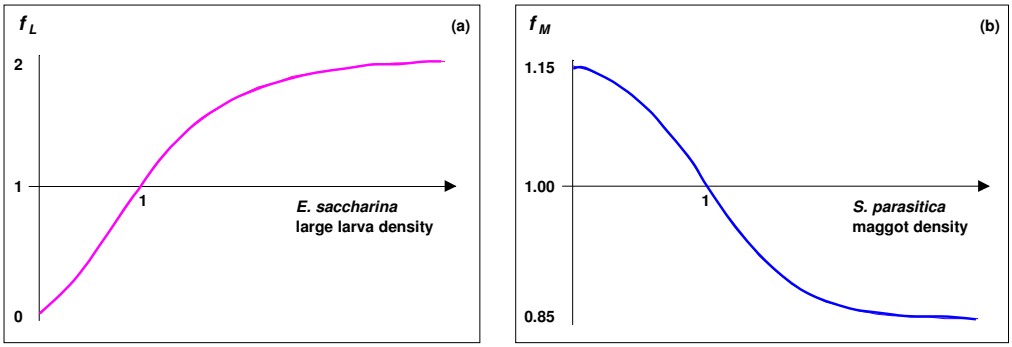

Figure 4.2: (a) Function representing the response of the specific parasitism rate to host density. (b) Function representing the response of the specific parasitism rate to parasitoid density.

4.2.2 The *E. saccharina* sector

The only stage in the *E. saccharina* life cycle that is affected by the presence of *S. parasitica* is the large larval stage. The modifications to the *E. saccharina* model developed in Chapter 3 needed to model the interaction between the host and the parasitoid are therefore limited to the equations describing large larva cohort populations. The other equations are left unchanged.

For the host-parasitoid model, the equation describing large larva cohorts in system (3.1) is re-written as

$$LLV_i(t+1) = (LLV_i(t) - PARLOSS_i(t)) \times \left(1 - LL_i^d(t) - LL_i^m(t)\right), \quad (4.9)$$

for each $i \in S_{\text{ll}}(t)$, where $PARLOSS_i(t)$ is the total number of members of the cohort that have died due to parasitism:

$$PARLOSS_i(t) = \sum_{j=i}^{t} p_{i,j}(t) \times PMR_i(t), \quad (4.10)$$

where $PMR_i(t)$ is the mortality rate caused by *S. parasitica* parasitism. The initial conditions given in equation (3.5) for populations of large larvae remain unchanged and are used as initial conditions for equation (4.9) in the host-parasitoid model.

The mortality rate $PMR_j(t)$ depends on the number of days spent by the parasitoids on host $LLV_i(j)$ by day t. $PMR_j(t)$ incorporates the time spent feeding on the host before the host dies, thereby introducing a delay between

the time *E. saccharina* larvae get attacked and the time they eventually die due to parasitism. We approximate the rate $PMR_j(t)$ as follows:

$$PMR_j(t) = f_{PMR}(t, j),$$

where the function f_{PMR} is given by

$$f_{PMR}(t,j) = \begin{cases} 0, & \text{if } DD_j^{\text{mg}}(t) < DD_{\text{min}}^{\text{mg}} \\ MGT_j^m(t), & \text{if } DD_j^{\text{mg}}(t) \geq DD_{\text{min}}^{\text{mg}} \end{cases} \tag{4.11}$$

That is, equations (4.9) and (4.11) say that we only allow parasitized *E. saccharina* larvae to live until the maggots feeding on them mature to *S. parasitica* pupae unless natural mortality takes its course before that. As pointed out earlier, if parasitized *E. saccharina* larvae pupate the maggots living on them continue to feed on the pupa. In the model, parasitized pupae will be considered to be dead and will not contribute to the total pupae population. Because *E. saccharina* pupae do not contribute to crop damage and because pupae that result from parasitized larvae die before maturing to moths, this does not affect the dynamics of the model for the intended purposes of the model. In other words, once *S. parasitica* maggot cohorts are established, their dynamics are described by the maggot equation in system (4.1) regardless of the condition of the parasitized *E. saccharina* larvae.

4.3 Calibrating the host-parasitoid model

According to Martin (2002), *S. parasitica* thrives in a tropical climate. The subtropical climate of the southern African sugar belt may thus impose lim-

itations to the establishment of *S. parasitica* in South Africa. Recoveries of parasitized *E. saccharina* larvae in certain areas of the sugar belt have however indicated that there is potential for the use of *S. parasitica* as a biological agent against *E. saccharina* in these areas. The simulations performed here are therefore limited to temperature scenarios identical to those experienced in these areas.

At present, not much field data has been collected on the success of *S. parasitica* as a biological control parasitoid of *E. saccharina*. Preliminary field trials (which are still ongoing), together with laboratory data were therefore used when calibrating the *S. parasitica* submodel of the host-parasitoid model. The *S. parasitica* parameters used in the host-parasitoid model are those given in Tables 4.1 and 4.2. In one field release trial, about 150 female *S. parasitica* flies were uniformly released into an area of the field measuring 0.47 ha every seven days, beginning when the crop in the field was about six months old. Field surveys later showed low percent parasitization of *E. saccharina* by *S. parasitica* (maximum of 2.1% for the region under consideration)(SASRI Entomology Department progress report, 1/4/2000 to 31/3/2001). This information was used when determining the specific parasitism rate SPR (set to 0.002 large larvae/maggot/day) and the multiplier functions f_L and f_M.

The host-parasitoid model was tested by first running it without parasitoids, concurrently with CANEGRO, using daily climatic and soil records from the area of Gingindlovu in KwaZulu-Natal to coincide with a crop cycle

beginning in November 1991. The area selected is where parasitism has been recorded (Conlong, pers. comm.). The simulation was done for a 1 ha field over a 24 month period. It was found that the larval population density reached a peak of 128 e/100s, which is not uncommon for a 2 year old field. We then proceeded to simulate a field experiment, releasing 320 female *S. parasitica* adults into the same field every seven days, starting when the crop age reached six months (this was done in order to simulate releases similar to those done in the field experiment whose data was used when calibrating the model). Results of the simulation show a maximum of 6.9% parasitization with larval densities peaking at a reduced 113 e/100s. The discrepancy between field and simulated percent parasitism could be because the timing of the survey may play a role in the numbers recovered as these fluctuate daily. It has been noted however that in experimental fields where *S. parasitica* has been released, even when no parasitism was recorded, *E. saccharina* numbers per 100 stalks were found to be lower indicating that parasitism did occur (SASRI Entomology Department progress report, 1/4/2000 to 31/3/2001).

4.4 Model validation

In the absence of field data on the interaction of *S. parasitica* and *E. saccharina*, not much can be said about the performance of the host-parasitoid model in as far as simulating actual field interactions is concerned. The host-parasitoid model will therefore only be used as a tool to test the rela-

tive impact of the frequency of *S. parasitica* releases, the number of females released and the timing of releases on the success of reducing *E. saccharina* infestation levels.

Chapter 5

Performance index

5.1 Introduction

In order to be able to compare the benefits from implementing the various management strategies, a crop damage index is defined that serves as an indicator of the damage caused by *E. saccharina*. The crop damage index is later linked to losses in revenue that can be expected if *E. saccharina* populations are left unchecked.

5.2 Crop damage index

At present, SASRI has no actual link between *E. saccharina* larvae counts and crop damage. Farmers are advised to harvest their crop if larval counts exceed 10e/100s without any knowledge about the other stages of the borer life cycle. For example, at the decision date, a field survey may indicate larval numbers below 10e/100s but if there are enough unhatched eggs and the conditions are conducive for *E. saccharina* growth, serious damage could be experienced when mills reopen three months later.

In this section, a damage index that is directly linked to the actual number of larvae that have been feeding on the sugarcane stalk since the crop was planted is proposed. To take into account the variation in larval activity at various temperatures, the damage index is also linked to the degree-days accumulated by the larvae. The damage index (denoted $D_{\text{ind}}(t)$) on any day t of the simulation is defined as the cumulative total of (large) larvae degree-days spent in the sugarcane stalk up to day t. That is, on each day of the simulation, the crop damage index is updated as follows:

$$D_{\text{ind}}(t) = D_{\text{ind}}(t-1) + TLLV(t) \times \max\left\{0, T_{\text{ave}}(t) - T_{\text{th}}^{\text{ll}}\right\} \times 1 \text{ day}, \quad (5.1)$$

with initial condition

$$D_{\text{ind}}(0) = 0.$$

Because $TLLV(t)$ is given in terms of e/100s, the units of D_{ind} are (e/100s)$\cdot^{\circ}$C $\cdot$ d.

5.2.1 Determining crop damage due to *E. saccharina*

Damage (i.e. stalk bored) by *E. saccharina* was determined from data generated by varietal sugarcane screening trials routinely conducted at SASRI. Results of the performance of control (commercial) varieties in a total of 20 trials performed over four years (five trials per year) were used. The method used is given in detail in Keeping et al. (2003) and is summarized here in order to give insight into how the damage index defined is linked to stalk length bored.

The screening trials were conducted in shade houses in order to (1) enable controlled water stressing of plants, which is not possible outdoors, and (2) protect plants from feral infestations of *E. saccharina*. The varieties were planted into replicated pot trials (6 seedlings per pot) where they were drip-irrigated and fertilized at the same rate. At 8 months (or when the crop had matured), the plants were moisture stressed by reducing irrigation in a staged fashion until there were no fewer than 5 green leaves per stalk.

After a month of stressing, the pot trials were artificially inoculated with *E. saccharina* eggs (between 100 and 300 eggs) provided by the SASRI Insect Rearing Unit. At the time of inoculation, many of the eggs were in the 'black head' stage of development and hatched within a day. Infestations were allowed to develop over a period required to accumulate $500°\mathrm{C} \cdot \mathrm{d}$, by which time the majority of larvae had developed to the late instar (V - VI) or, less commonly, the pupal stage (Way, 1995). Pre-set Tempest® degree-day

devices (Insect Investigations, Cardiff) were used to measure development to $500°C \cdot d$ with a threshold temperature of 10°C. At that point, trials were harvested and all stalks were dissected by experienced inspectors to record the following information: length of stalk, length of stalk bored, number of internodes per stalk, number of internodes bored, number of larvae, number of pupae and pupal cases, mass of larvae and mass of pupae. The damage and insect parameters were subsequently used in a calculation which produces a resistance rating score of between 1 and 9 for each variety. Control varieties from which the data were obtained, vary in borer resistance from highly susceptible (N11, N26, N16), through moderately susceptible (NCo376), to moderately resistant (N12) and resistant (N21).

For the purposes of the investigations to be carried out in this study, data on the stalk length bored and the total number of larvae and pupae recovered are used to determine the stalk length bored per larva per degree-day. Since there is only a single generation of borers, the larvae and pupae collected at the end of each trial are responsible for the total damage recorded. Hence, their number can be directly related to the damage produced over a $500°C \cdot d$ period of development or, on average, over the entire period of larval development.

The length of stalk bored per large larva per degree-day was calculated from data collected from these trials. Table 5.1 shows the length of stalk bored per larva per degree-day for various crop varieties.

The results shown in Table 5.1 suggest that the stalk length bored per large

Table 5.1: Length of stalk bored per large larva per °C · d for various crop varieties. Source: Calculated from *E. saccharina* Resistance Trials Raw Data, Entomology Department, SASRI.

Variety (ρ)	Stalk Length Bored (mm/e/°C · d)	Std Dev.	Range (90% Conf. Int.)
N21 (1)	0.109	0.092	0.087 - 0.132
N33 (2)	0.084	0.027	0.066 - 0.101
N12 (3)	0.103	0.072	0.085 - 0.121
N17 (4)	0.104	0.046	0.085 - 0.123
NCo376 (7)	0.125	0.072	0.105 - 0.144
N11 (9)	0.099	0.057	0.084 - 0.115
N26 (9)	0.093	0.053	0.080 - 0.105
Overall	0.105	0.069	0.097 - 0.112

larva per °C · d is independent of the variety grown, i.e., once *E. saccharina* larvae successfully bore into the sugarcane stalk, they more or less consume the same amount of tissue regardless of the crop variety. This was confirmed by performing an analysis of variance (ANOVA) on the raw data which gave an F value of 0.934 (< 1). Since the experiments from where the data was collected were not set up to investigate the influence of crop variety on the length of stalk bored by *E. saccharina*, more research needs to be conducted on this matter before any definite conclusions can be reached regarding the stalk length bored per larva per °C · d. What is clear at present is that crop variety affects the number of *E. saccharina* borer recoveries; more larvae are recovered from highly susceptible varieties than are recovered from highly resistive varieties.

For the purposes of the work to be done here, the overall average of the stalk

length bored per larva per °C · d taken over all the control varieties is used. The average for stalk length bored per larva per degree-day was found to be 0.105 mm/e/°C·d and is the value that will be used from here onwards when calculating the length of stalks bored by *E. saccharina* in the model.

5.2.2 Determining stalk length bored in the model

The model calculates the average length of stalk bored (SLB) by day t of the simulation using the damage index on day t and the average length of stalk bored per larva per °C · d (given above):

$$SLB(t) = \sigma \times \frac{D_{\text{ind}}(t)}{100} \quad (\text{mm/stalk}) \tag{5.2}$$

where $\sigma (= 0.105$ mm/e/°C · d) is the stalk length bored per large larva per degree-day.

In order to estimate the percent stalk length bored ($\%SLB(t)$) on day t of the simulation, the stalk length calculated in the CANEGRO model is used together with $SLB(t)$:

$$\%SLB(t) = \frac{SLB(t)}{SL(t)} \times 100\%,$$

where $SL(t)$ is the average length of stalk on day t of the simulation as calculated by the CANEGRO model.

5.3 The RV formula for sugarcane payment

As mentioned in Chapter 1, the South African Sugar Industry has, since the 2000/2001 sugarcane season, adopted a sugarcane payment system based on the 'quality' of the crop delivered to the mill rather than on the quantity of sucrose in the consignment delivered.

The derivation of the formula for sugarcane payment is presented in Murray (2000). It is a modification of the *Estimated Recoverable Crystal* (ERC) formula proposed by van Hengel (1974) and is known as the *Recoverable Value* (or RV) formula:

$$RV = S - dN - cF, \tag{5.3}$$

where

S	=	percent sucrose present in sugarcane delivered
N	=	percent non-sucrose present in sugarcane delivered
F	=	percent fibre present in sugarcane delivered
d	=	the loss of sucrose per unit of non-sucrose. Credit is given for the value of molasses recovered per unit of non-sucrose
c	=	the loss of sucrose in sugar production per unit of fibre

The parameters c and d are mill specific and only vary slightly from mill to mill. For a typical mill, $c = 0.0198$ and $d = 0.5506$ (Peacock and Schorn, 2002). These values will be used in all calculations of RV that follow.

Of the factors S, N and F in the RV formula, the sugarcane growth model CANEGRO currently only calculates the amount of sucrose (S) present in the crop. For illustrative purposes, Bezuidenhout (pers. comm.) suggested that for mature sugarcane, fibre (F) can be kept constant at 12.9% and that the percent non-sucrose (N) be estimated using the relationship

$$N = 4.657 - 0.173S$$

The RV formula can then be re-written as follows:

$$RV = S - dN - cF = S - d(4.657 - 0.0173S) - 12.9c = \alpha S - \beta \quad (5.4)$$

where $\alpha = 1 + 0.0173d \approx 1.0095$ and $\beta = 4.657d + 12.9c \approx 2.8196$.

5.3.1 Calculating the effect of *E. saccharina* on RV

Since the larval feeding habit of *E. saccharina* is estimated to cause about 0.1% loss in recoverable sucrose for every 1% of sugarcane stalks damaged (see, e.g., Smaill and Carnegie, 1979; 2000/2001 SASRI Entomology Department progress report, page 56), in addition to having to ensure that the sugarcane crop delivered to the mill has relatively low levels of fibre and non-sucrose, sugarcane farmers have to minimize damage due to *E. saccharina* as this will further reduce percent sucrose in their crop, thereby lowering its RV.

When *E. saccharina* are present, we recalculate the percent sucrose calculated

by the CANEGRO model as follows:

$$S_e = S \times (1 - 0.001 \times \%SLB),$$

where S_e is the reduced amount of sucrose when *E. saccharina* are present. Let $f_{SLB} = \%SLB/100\% = SLB/SL$ represent the fraction of stalk length bored. When *E. saccharina* are present, the RV formula then becomes

$$RV_e = \alpha S_e - \beta = \alpha S(1 - 0.1 f_{SLB}) - \beta \tag{5.5}$$

By using Equations 5.4 and 5.5, losses in RV caused by the presence of *E. saccharina* can be compared, and improvements in RV when the various control measures are implemented can also be investigated. The loss in RV due to *E. saccharina* will be given by

$$RV_{\text{loss}} = RV - RV_e = 0.001\alpha \times \%SLB = 0.1\alpha f_{SLB} \tag{5.6}$$

Chapter 6

Policy analysis

6.1 Introduction

In this chapter, the model is used to investigate various management strategies aimed at reducing damage to the sugarcane crop due to *E. saccharina*. The management strategies to be investigated include harvesting decision, biological control strategies and insecticide application strategies. At present, biological control and insecticide application strategies are still in the research stage and have not yet been approved for implementation by farmers. The means of control of *E. saccharina* currently available to sugarcane farmers are to plant resistant sugarcane varieties, to harvest early before infestation levels become too high, to apply less nitrogenous fertilizer and to practice good field hygiene.

6.2 Harvesting decision

Sugarcane may be harvested from as early as age 11 months but it can be left unharvested for longer as sucrose content increases with age. If, however, *E. saccharina* is present, the sucrose yield is greatly affected, as *E. saccharina* levels also increase with age. The farmer may then need to harvest sooner rather than later. During the milling season which runs from April to November, the farmer monitors (among various other factors) the damage to the crop due to *E. saccharina*. If the damage reaches a certain critical level, the crop is harvested. In late planted crop (i.e. crop planted near

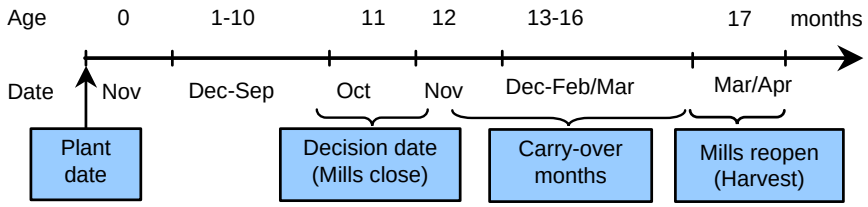

Figure 6.1: Late harvest crop and the carry-over decision.

the month of November), a decision has to be made the following November (when the crop is about 12 months old) before mills close, whether to harvest or carry the crop over to March when mills reopen (see Figure 6.1). This decision is known as the 'carry-over decision' and the crop carried over is usually referred to as 'carry-over crop' or 'carry-over cane'. The carry-over decision is based on crop damage at the decision date and projected damage when mills reopen. The model can be used to aid this decision by running it for actual temperature data up to mill closure and historical temperature

data over the carry-over period to determine possible losses by the time mills reopen. The impact of the other control measures can also be investigated for the carry-over period.

Initially, an investigation into the effect of planting date on the percent stalk length bored recorded at the decision date and when mills reopen was carried out. The model was run using temperature data collected over a 36 year period for crop cycles beginning in July, August, September, October, November and December. Crop conditions for these cycles were determined from running the CANEGRO model using temperature and weather data corresponding to the dates considered. At the decision date, the crops are aged 16, 15, 14, 13, 12 and 11 months respectively, and would be ready for harvesting if damage was found to be too high. The results of these simulations are presented in Table 6.1.

Table 6.1: Mean percent stalk length bored and the corresponding standard deviations for crop cycles beginning in July, August, September, October, November and December.

		Jul	Aug	Sept	Oct	Nov
Decision Date (Nov)	Mean $\%SLB$	7.0	6.5	4.5	2.1	1.4
	S.D.	7.68	7.85	5.39	2.24	1.35
Mills reopen (Mar)	Mean $\%SLB$	20.36	18.65	12.71	6.98	5.00
	S.D.	24.38	24.44	16.58	10.73	8.30

In order to determine the relationship between crop age and the percent stalk length bored, the model was run concurrently with the CANGRO model for the above data sets for two year crop cycles (in general, sugarcane will never

be allowed to mature beyond 24 months). The maximum percent stalk length bored that can be expected at confidence levels of 90%, 95% and 99% against crop age is shown in Figure 6.2. Here, a confidence level of 90% means that the probability that the percent stalk length bored is below the given value is 0.9.

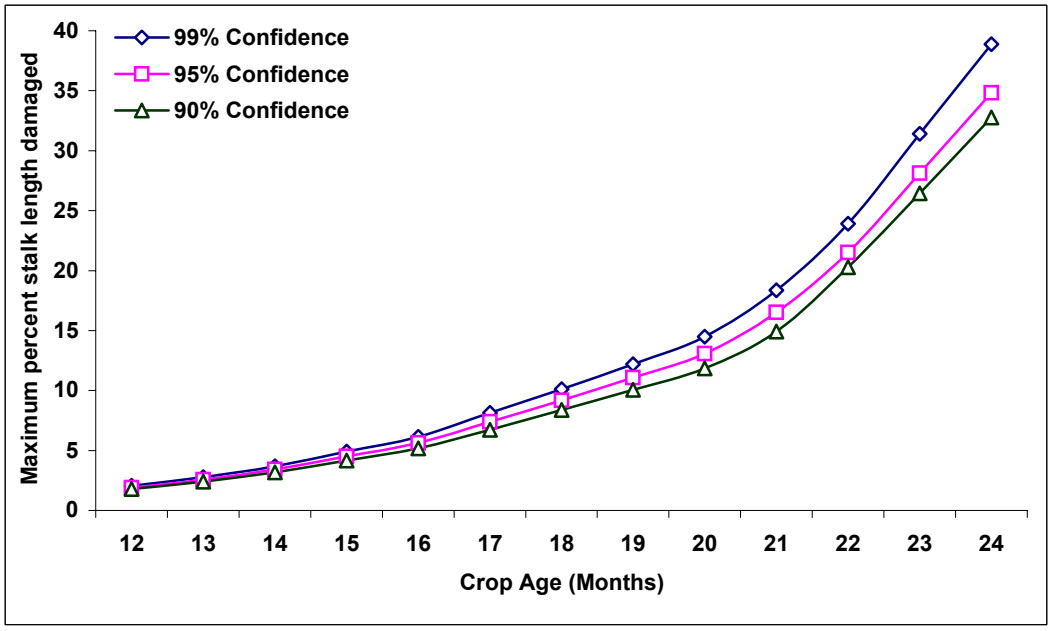

Figure 6.2: The expected minimum percent stalk length bored when mills reopen (at 95% confidence level) based on a known value of percent stalk length bored at the decision date.

There are at least two ways that model results of the type shown in Table 6.1 can be used as a carry-over decision aid by farmers. One is related to the percent stalk length bored and the other is related to the percent RV of the crop. These decision criteria are not yet used in the South African Sugar

Industry and are suggested here as alternatives to the one currently in use.

The carry-over decision is currently based on field surveys of e/100s and the crop variety grown. If the crop variety grown is highly susceptible to *E. saccharina* attack, crop carry-over is not recommended. For crops that are less susceptible, crop carry-over is recommended if field surveys indicate levels below 20e/100s. This does not however give a true indication of the stalk damage incurred, as *E. saccharina* numbers can fluctuate widely in the field from one week to the next and the timing of the survey could lead to misleading information on future infestation levels. A reading of percent stalk length bored may give a better picture of damage due to *E. saccharina*.

6.2.1 Using percent stalk length bored to aid the carry-over decision

A decision based on the percent stalk length bored would involve first deciding what level of percent stalk length bored would be undesirable and then calculating the risk that this level would be reached during the crop carry-over period. For example, suppose that percent stalk length bored exceeding 20% is undesirable. Based on the results given in Table 6.1, the probability that $\%SLB > 20\%$ when mills reopen for each of the crop cycles considered is given in Table 6.2. Depending on the risk the grower is prepared to take a decision can be made whether to carry the crop over or not based on results found using the above procedure.

Table 6.2: The probability that $\%SLB > 20\%$ when mills reopen for the crop cycles considered in Table 6.1.

	Jul	Aug	Sep	Oct	Nov
$Pr(\%SLB > 20\%)$ in March	50.6%	47.8%	33.0%	11.3%	3.5%

For the crop cycles considered in Table 6.1, the maxima of percent stalk length bored that can be expected at the decision date and when mills reopen, based on 90%, 95% and 99% confidence levels, are given in Table 6.3. For example, for the November crop cycle, we can be 95% confident that the percent stalk length bored will be below 18.6% (and hence, below the undesirable level of 20%) when mills reopen.

Table 6.3: The maximum percent stalk length bored that can be expected at the decision date and when mills reopen at 90%, 95% and 99% confidence levels for the crop cycles considered in Table 6.1.

	Max. $\%SLB$ (Nov)			Max. $\%SLB$ (Mar)		
	90%	95%	99%	90%	95%	99%
July Crop	16.9	19.6	24.9	51.6	60.3	77.2
August Crop	16.6	19.4	24.8	49.9	58.7	75.6
September Crop	11.4	13.3	17.0	33.9	39.9	51.3
October Crop	5.0	5.8	7.3	20.7	24.6	32.0
November Crop	3.1	3.6	4.5	15.6	18.6	24.3

It should be stated here that the results shown in Tables 6.1 to 6.3 do not reflect industry-wide scenarios but are specific to a certain area and a particular varietal resistance rating to *E. saccharina*. They are presented here for illustrative purposes only. As data for weather and soil conditions can vary from one area to the next, the crop conditions that determine attack

rates by the pest will differ (see results of $\%SLB$ for another region where only the soil type is varied in Table 6.4). It would therefore be necessary for the user of the model to ensure that the CANEGRO output data and the temperature data used correspond to the area under consideration.

Table 6.4: $\%SLB$ at decision date and when mills reopen for a crop cycle beginning in November on different soil types. Weather data is the same in all cases.

	Soil Type 1		Soil Type 2		Soil Type 3	
	$\%SLB$		$\%SLB$		$\%SLB$	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Nov	0.78	0.78	0.97	0.87	1.19	0.96
Mar	2.10	2.26	3.13	3.35	4.45	4.2

Suppose now that the farmer has a measure of the percent stalk length bored at the decision date and wants to find out what the projected percent stalk length bored will be by the time mills reopen. In order to answer this question, weather data sets were prepared such that they were fixed up to the decision date and varied using historical weather data for the carry-over period. By running the CANEGRO model for these weather data scenarios and using its crop condition output in the *E. saccharina* model, various possibilities of percent stalk length bored when mills reopen can be simulated for a particular fixed reading of percent stalk length bored at the decision date. The results of these simulations are shown in Table 6.5.

With the type of results given in Table 6.5, given percent stalk length bored at the decision date, the expected minimum and maximum percent stalk length

Table 6.5: Expected mean %*SLB* and standard deviation when mills reopen given a particular level of %*SLB* at the decision date.

%*SLB* (Nov)		2.8	5.5	8.3	11.0	13.5
Expected	Mean:	8.4	16.9	25.3	33.7	42.1
%*SLB* (Mar)	S.D.:	2.24	4.48	6.72	8.95	11.19

bored when mills reopen based on the risk the sugarcane grower is willing to take can be found. The projected minimum and maximum percent stalk length bored for the results of Table 6.5 at 95% confidence levels are shown in Figure 6.3. The expected maximum and minimum percent stalk length bored for intermediate values of percent stalk length bored at the decision date can be found by interpolation. For example, suppose the sugarcane grower is only willing to take a risk of 5%. Using interpolation and the results of Figure 6.3, it is found that the value of percent stalk length bored at the decision date whose expected corresponding value when mills reopen will be above the undesirable 20% level at a risk of 5% is 5.98% $\approx$ 6%. That is if a grower is only willing to take a 5% risk, the cut-off level at the decision date would be 6%. If the undesirable level was 30%, the cut-off level would be approximately 9% at a risk of 5%.

6.2.2 Using percent RV to aid the carry-over decision

Carry-over decision based on percent RV would involve determining the losses in RV that would be incurred if the crop was severely attacked by *E. saccharina* during the carry-over season.

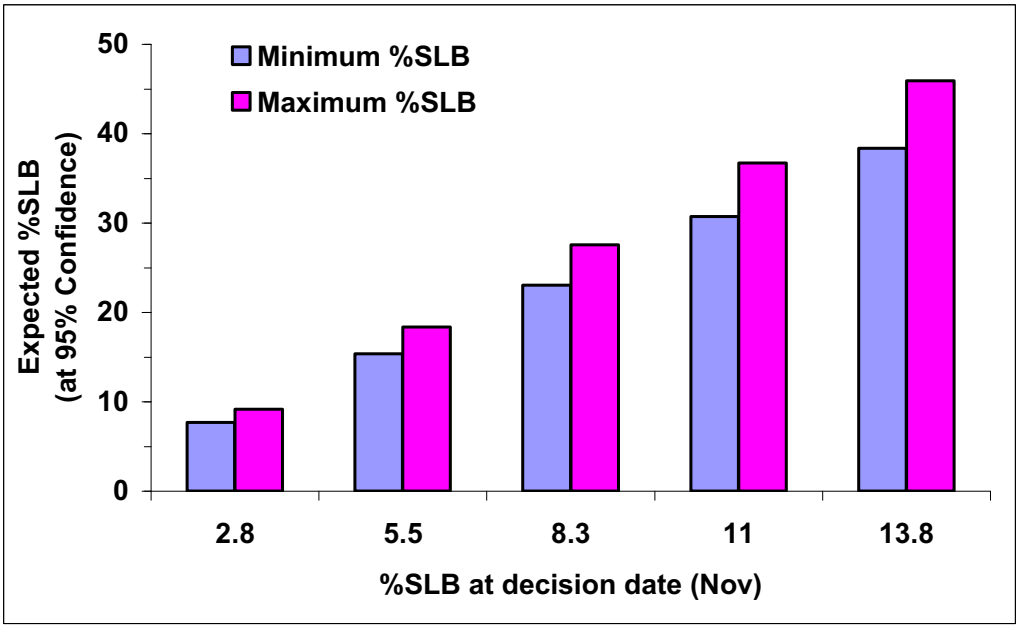

Figure 6.3: The expected minimum and maximum percent stalk length bored when mills reopen (at 95% confidence level) based on a known value of percent stalk length bored at the decision date.

Let t_c and t_o correspond to mill closure and mill re-opening times respectively. Let $S(t_c)$ and $S(t_o)$ represent the percent sucrose present (in the absence of *E. saccharina*) at mill closure and when mills reopen, respectively. Based on the RV formula, the grower would be advised to carry the crop over provided it is expected that $RV_e(t_o) > RV_e(t_c)$. This, together with equation (5.6), effectively means that the grower can expect an increase in RV between mill closure and when mills reopen provided that

$$f_{SLB}(t_o) < \frac{S(t_c)}{S(t_o)}(f_{SLB}(t_c) - 10) + 10, \tag{6.1}$$

where $f_{SLB}(t_o)$ is the projected fraction of stalk length bored when mills reopen and $f_{SLB}(t_c)$ is fraction of stalk length bored at mill closure determined,

respectively, from $\%SLB(t_c)$ and $\%SLB(t_o)$ calculated in the model.

As an illustration of how to use inequality (6.1) to aid the carry-over decision, the simulation results of percent stalk length bored presented in Table 6.1 and the corresponding percent sucrose levels simulated by the CANEGRO model are used. The average percent sucrose levels for these crop cycles are presented in Table 6.6.

Using the mean values given in Tables 6.1 and 6.6, the left-hand-side (LHS) and right-hand-side (RHS) of inequality (6.1) for each of the crop cycles are presented in Table 6.7.

Table 6.6: Mean percent sucrose and the corresponding standard deviations at the decision date and when mills reopen for crop cycles beginning in July, August, September, October, November and December.

	Jul	Aug	Sept	Oct	Nov
$S(t_c)$	11.15	10.92	10.74	10.37	9.52
S.D.	2.13	2.13	2.16	2.24	2.40
$S(t_o)$	12.92	12.82	12.76	12.57	12.20
S.D.	0.84	0.89	0.89	1.08	1.33

Table 6.7: The left-hand-side and right-hand-side of inequality (6.1) for each of the crop cycles beginning in July, August, September, October, November and December based on the results of Tables 6.1 and 6.6 .

	Jul	Aug	Sept	Oct	Nov
LHS	0.204	0.186	0.127	0.070	.050
RHS	1.42	1.54	1.62	1.76	2.21

The results of Table 6.7 show that inequality (6.1) is satisfied for all the crop

Table 6.8: The expected increases in RV if the crop is carried over for each of the crop cycles considered in Table 6.7

	Jul	Aug	Sept	Oct	Nov
% Gain in percent RV	19	21	24	28	39

cycles under consideration. It would therefore be recommended that these crops should be carried over as an increase in RV can be expected. The expected increases in percent RV are shown in Table 6.8.

6.3 Insecticide application

The control of *E. saccharina* using insecticides is normally undertaken soon after a moth peak is observed in the field. The *E. saccharina* stage considered to be most vulnerable to insecticides is the small larva stage. Of this stage, the most vulnerable are the first instar larvae because soon after eclosion, they disperse from the oviposition sites, leaving them exposed. Second and third instar larvae are less exposed but are still vulnerable as they spend their time scavenging on the outside of the sugarcane stalk. The large larvae are considered to be well protected from insecticides as they spend their time hidden inside the sugarcane stalk, feeding on the soft tissue inside. The insecticide kill rate is thus a function of the physiological age (in $^{\circ}\mathrm{C}\cdot\mathrm{d}$) of the small larvae. It is also a function of the number of days elapsed since the day of insecticide application as the effect of the insecticides applied decreases as time goes on. It is estimated that insecticide effect decreases slowly at first

and more rapidly later, following the shape of the function

$$DECAYF(n) = \left(1 - \left(\frac{n}{d_{\text{maxeff}}}\right)^3\right), \tag{6.2}$$

(Leslie, pers.comm.) where n is the number of days elapsed since application of insecticide and d_{maxeff} is the maximum number of days that the insecticide remains effective in the field.

As data on insecticide kill rate are not currently available at SASRI, the following kill rates will be assumed for illustrative purposes: 60% for first instar larvae ($DD_i^{\text{sl}}(t) \leq 80°\text{C} \cdot \text{d}$), 40% for second instar larvae ($80°\text{C} \cdot \text{d} < DD_i^{\text{sl}}(t) \leq 150°\text{C} \cdot \text{d}$) and 20% for third instar larvae ($DD_i^{\text{sl}} > 150°\text{C} \cdot \text{d}$). These kill rates are then adjusted to account for the decay in insecticide effect with time by multiplying them by the function $DECAYF(n)$ given in Equation (6.2).

The aim here is to find the relationship between the duration of the effect of the insecticide applied (d_{maxeff}) and the reduction in percent stalk length bored ($\%SLB$) and hence the reduction in losses in RV (RV_{loss}). Long lasting insecticides may be cheaper to use in terms of labour costs and may even have a better kill rate, but any dose of a well timed application may result in a better kill rate.

Insecticides whose effect lasts for two weeks, four weeks and eight weeks will be investigated. In order to achieve this, simulations were run for crop cycles beginning in August over the period from 1966 to 2000. Weather data for this

period was used in the CANEGRO model to simulate the crop conditions used in the *E. saccharina* model. A simulated insecticide application was effected whenever moth peak densities exceeded 75 in 10 000 stalks.

The mean and standard deviation of the percent reduction in percent stalk length bored at the decision date and when mills reopen are presented in Table 6.9.

Table 6.9: Mean percent reduction in percent stalk length bored and the corresponding standard deviations for insecticide effect duration of 14 days, 28 days and 56 days.

	14 Day Effect		28 Day Effect		56 Day Effect	
	Nov	Mar	Nov	Mar	Nov	Mar
Mean % reduction in $\%SLB$	33.2	72.6	37.3	78.2	39.3	81.4
Standard deviation	24.7	17.6	24.4	14.3	25.4	13.7

The minimum percent reduction in percent stalk length bored that can be expected at the various levels of confidence that the various insecticides can achieve is given in Figure 6.4. From the results shown in Figure 6.4, that the insecticides whose effect lasts for 56 days achieves the best percent reduction in percent stalk length bored. This, and the fact that longer lasting insecticides require less labour because they are less frequently applied would make them ideal for the control of *E. saccharina* once the use of insecticides has been approved. Before any recommendations can be made, more research has to be done on how the insecticides affect other insects in the field and more importantly, how *E. saccharina*'s natural enemies are affected because

this could have serious consequences on future outbreaks of the pest.

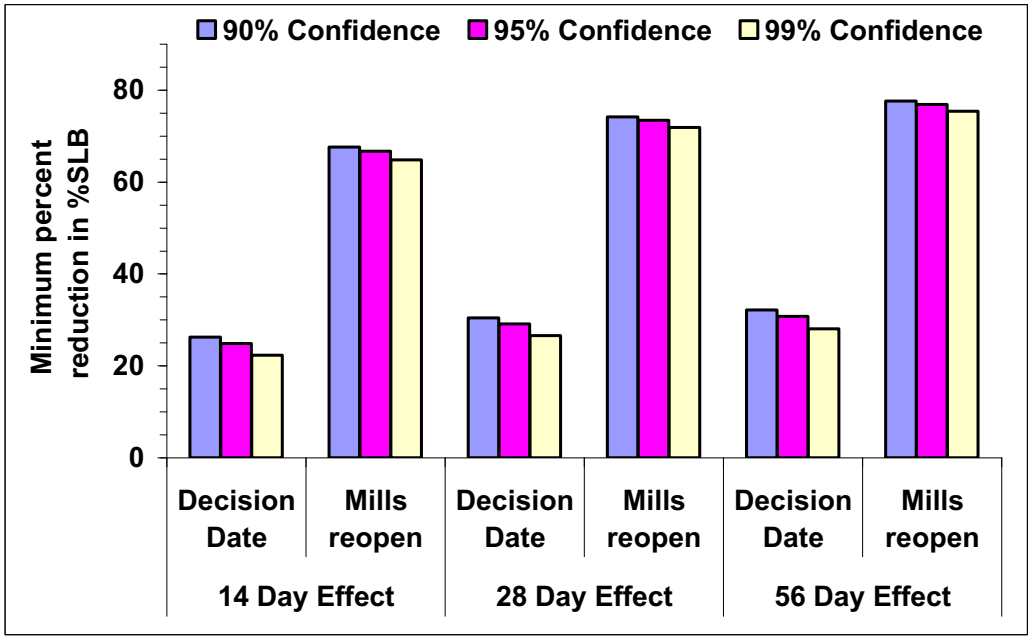

Figure 6.4: Minimum percent reduction in percent stalk length bored for various durations of insecticide effect at various levels of confidence.

The relationship between the duration of insecticide effect on percent RV is presented in Table 6.10. The maximum and minimum percent gains in RV (at 95% confidence) that can be expected from application of insecticides with the various duration of effect are shown in Figure 6.5.

From the results of Table 6.10 and Figure 6.5 it is clear that gains in percent RV are very similar regardless of the duration of insecticide effect. It would have been useful to compare the gains in RV, as calculated in the model, with the costs associated with insecticide application to be able to analyze

Table 6.10: Mean percent gains in percent RV and the corresponding standard deviations for insecticide effect duration of 14 days, 28 days and 56 days.

	14 Day Effect		28 Day Effect		56 Day Effect	
	Nov	Mar	Nov	Mar	Nov	Mar
Mean % gains in RV	0.82	3.13	0.85	3.32	0.89	3.31
Standard deviation	1.26	3.96	1.28	4.04	1.36	4.09

the costs and benefits of insecticide application. Unfortunately, no such data are available. In the absence of such data, a recommendation would be based on reduction in percent stalk length bored, percent gains in RV as well the assumption that labour costs would be lower when applying longer lasting insecticides. All these factors and the results of the simulations indicate that the longer lasting insecticides would be preferable.

6.4 Biological control

In this section, the biological control model developed in Chapter 4 is used in order to test the magnitude, frequency and timing of *S. parasitica* releases on percent stalk length bored and RV.

In order to test the response of the percent stalk length bored to changes in magnitude of *S. parasitica* adults released, simulations were performed where various numbers of adult *S. parasitica* females were uniformly released into a six month old field and noted the percent stalk length bored at the end

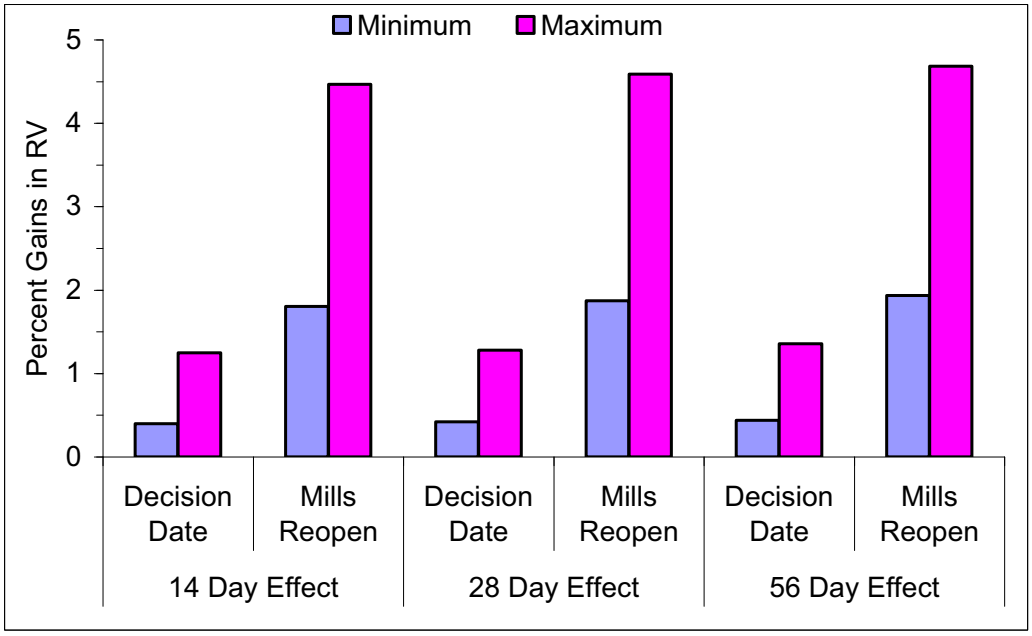

Figure 6.5: Minimum and maximum percent gains in RV at 95% confidence level for the various durations of insecticide effect.

of the simulation (at 24 months). The simulations performed were for single releases of parasitoids.

The results of simulating single releases of parasitoids were not very encouraging. Firstly, the percent stalk length bored recorded at the end of the simulations was only marginally reduced, even when the magnitude of release was greatly increased (see Figure 6.6). Secondly, there was no establishment of parasitoids on the field even when the number of female parasitoids released was as high as 20000. Was this due to the fact that the parasitoids were released during the cold month of May as this was when the crop reached an age of six months?

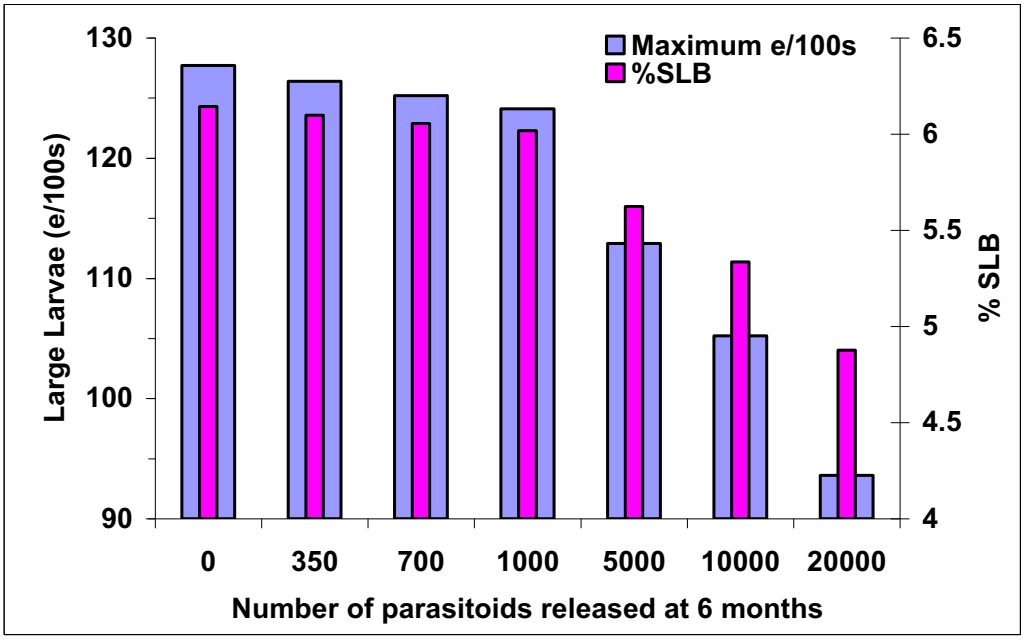

Figure 6.6: The relationship between the magnitude of a once-off parasitoid release and both percent stalk length bored and peaks of large larvae.

To test if this was indeed the case, simulations of once-off releases beginning in August (9 month old crop), November (12 month old crop), February (15 month old crop) were performed. These simulations confirmed our suspicions as new generations of flies were produced within the system - two new generations for an August release of 350 *S. parasitica* flies, two new generations for a November release of 350 *S. parasitica* flies and one new generation for a February release of 350 *S. parasitica* flies which was close to the start of the cold season (see Figure 6.7).

Note how the early August release results in smaller new generations than the new generations from the November release. This is because the temper-

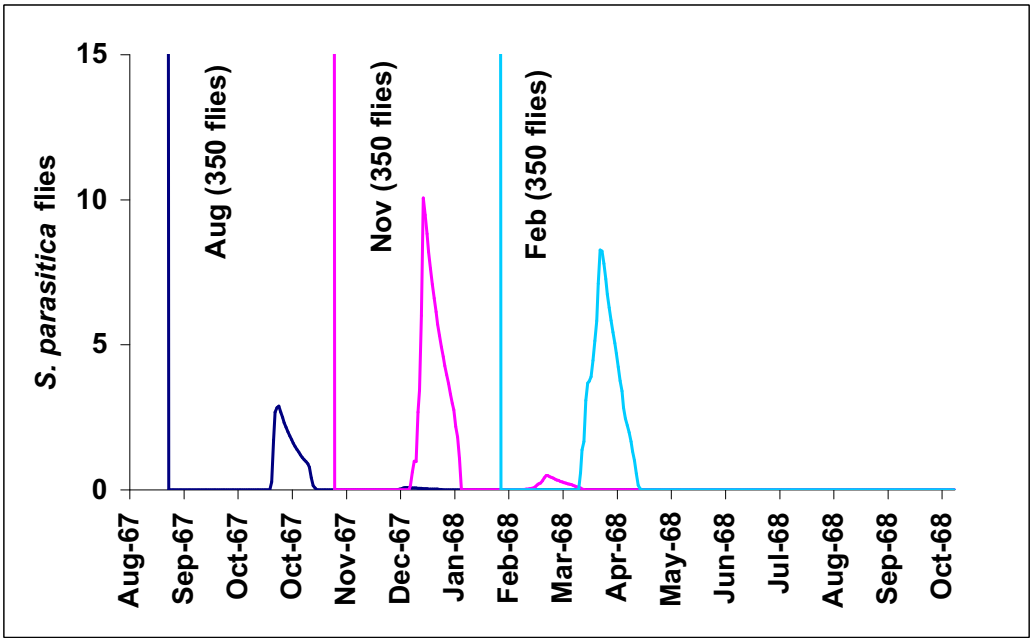

Figure 6.7: The effect of release date season on future generations of *S. parasitica*.

atures in early August are still low. The February release only has one new generation because this generation is close to the cold season and as noted, recoveries during the cold season are non-existent. It is disappointing to note that survival of *S. parasitica* under the conditions simulated here is very low as each new generation came at a much lower density. These results suggest that more effective releases of *S. parasitica* would be those done during the hot season of the year. A summary of the relationships between percent stalk length bored at the end of the simulation period and the magnitude and timing of once-off releases of adult *S. parasitica* females is shown in Figure 6.8.

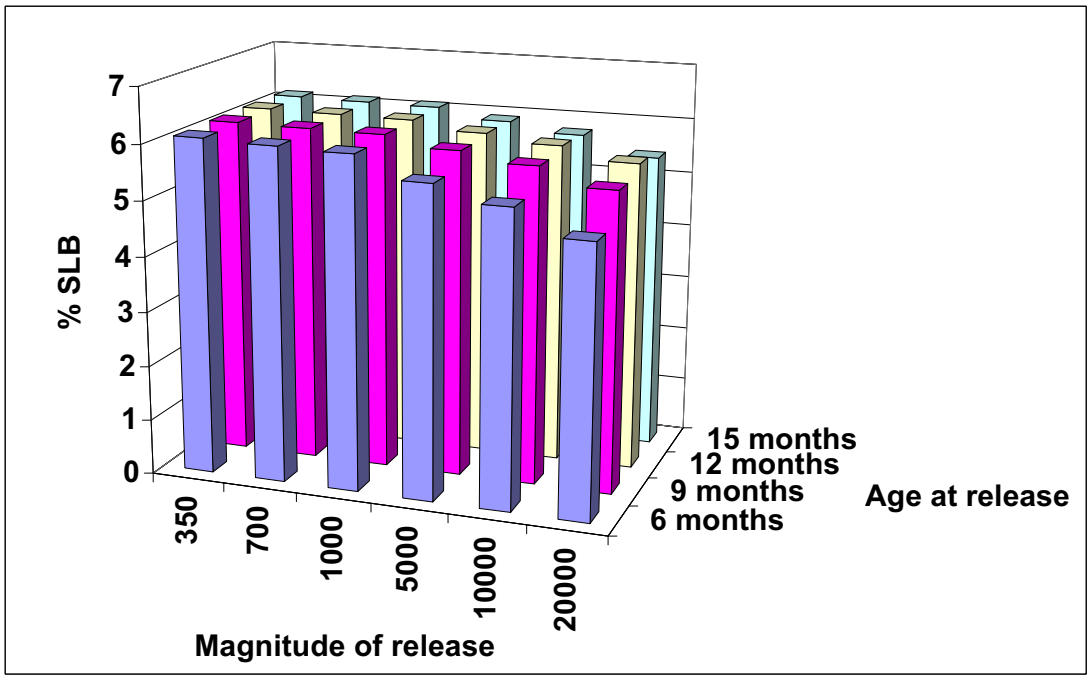

Figure 6.8: The relationships between percent stalk length bored at the end of the simulation period and the magnitude and timing of a once-off release of adult *S. parasitica* females.

Next, the relationships between the percent stalk length bored at the end of the simulation period and the frequency and timing of adult *S. parasitica* female releases into the field were investigated. *S. parasitica* adult longevity is between three to 41 days with most of the population surviving for about 23 days (Martin, 2002). It was therefore decided to begin by simulating the release of 350 adult *S. parasitica* females every 23 days, beginning when the crop had reached ages of 6, 9, 12 and 15 months. The percent stalk length bored at the end of each simulation was noted. Results showed an improvement in the reduction in stalk length bored when compared with

that of a once-off release of the same magnitude. The results also indicated that the sooner the the releases are carried out, the higher the reduction in percent stalk length bored at the end of the simulation (see Figure 6.9).

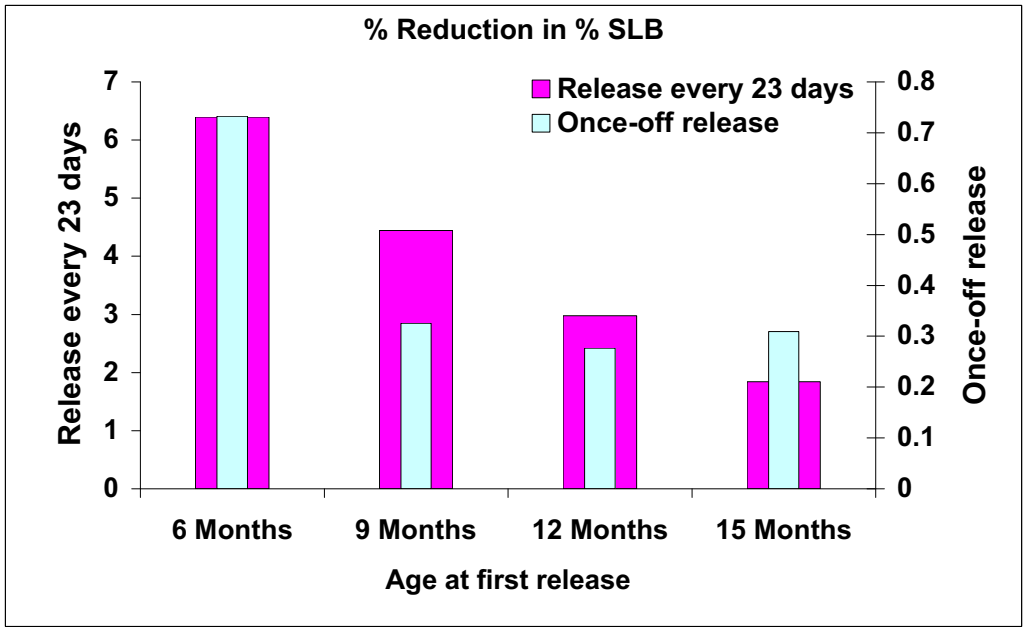

Figure 6.9: Reduction in percent stalk length bored from releasing 350 adult *S. parasitica* females once-off or every 23 days, beginning at various crop ages.

Simulations were then performed for more frequent releases (every seven days, to coincide with the release frequencies currently being used by biological control researchers at SASRI (Conlong, pers. comm.)) and less frequent releases (every 41 days, being the maximum number of days *S. parasitica* adults can survive) in order to investigate the effect of release frequencies on the reduction in percent stalk length bored and the resultant gains in percent

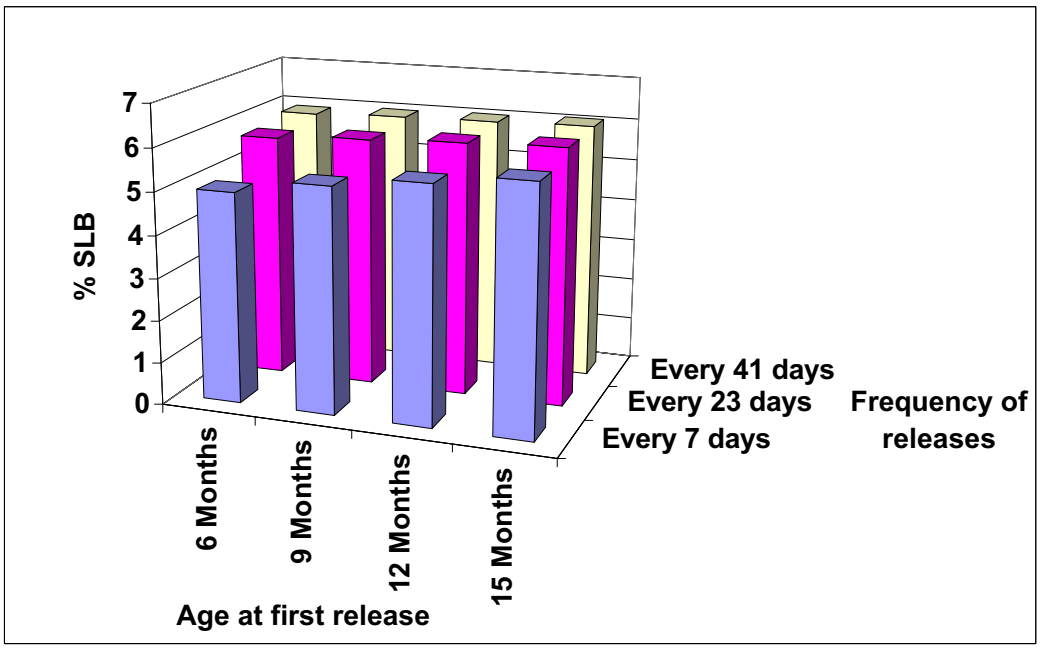

Figure 6.10: The relationship between the frequency of parasitoid release and percent stalk length bored at the end of the crop cycle when releases are first carried out at various crop ages.

RV. The number of adult *S. parasitica* females released in each case was 350. The percent stalk length bored at the end of each simulation for the various release frequencies is compared in Figure 6.10.

The results of these simulations indicate that the more frequent releases of parasitoids result in higher drops in percent stalk length bored and hence higher percent gains in percent RV. Table 6.11 shows the comparisons of reductions in percent stalk length bored and percent gains in percent RV for the different release frequencies.

Table 6.11: Percent reduction in damage index and corresponding gains in percent RV when 350 adult female *S. parasitica* are released into a six month old field at different frequencies when compared to no parasitoid releases.

Crop age at first release (months)	% Reduction in $\%SLB$ when released				% Gains in RV when released			
	Once	Every 7 days	Every 23 days	Every 41 days	Once	Every 7 days	Every 23 days	Every 41 days
6	0.7	19.1	6.4	3.8	2.4	62.4	20.9	12.4
9	0.3	13.7	4.4	2.7	1.1	44.8	14.5	8.7
12	0.3	9.7	3.0	2.0	0.9	31.5	9.7	6.5
15	0.3	5.9	1.8	1.2	1.0	19.3	6.0	3.9

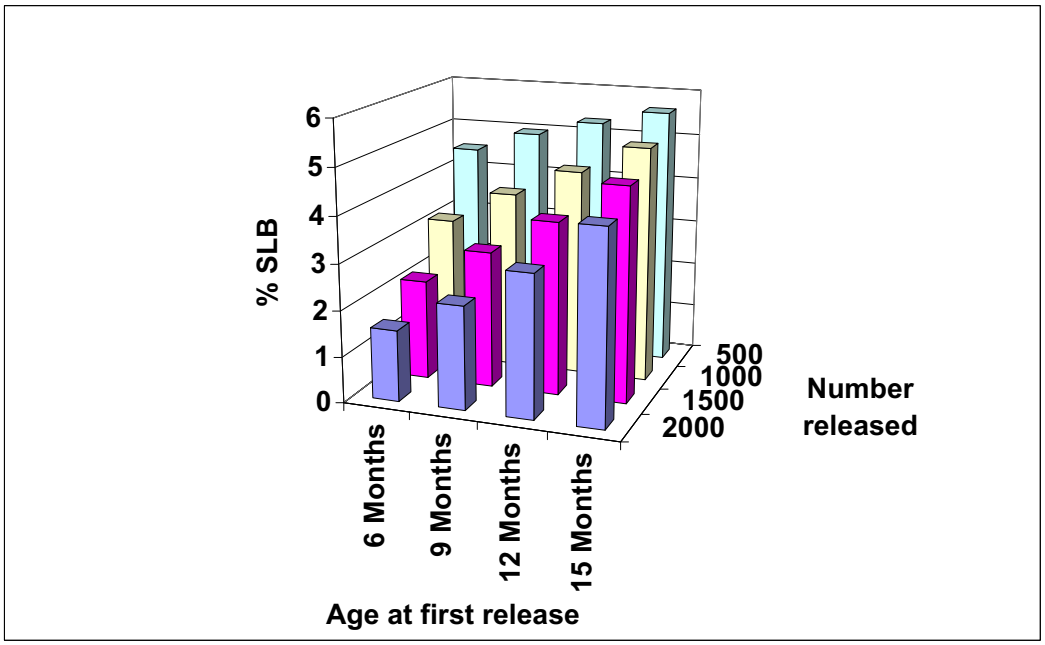

Figure 6.11: The relationship between the magnitude of a once-off parasitoid release and both percent stalk length bored and peaks of large larvae.

A recommendation on which parasitoid release strategy is best would have to take the costs of each release into account. For example, releasing 350

parasioids every seven days from age six months would require 79 releases by the end of the simulation period. The percent gains in RV that would be realized as a result of these releases was found to be about 62%. A similar release every 23 days would require 24 releases by the end of the simulation, resulting in about 21% gains in RV. In terms of percent gains in RV per release, releasing parasitoids every 23 days produces better results than releasing them every 7 days.

In order to investigate the relationship between the magnitude of releases combined with the frequency of releases on the percent stalk length bored at the end of the crop cycle, simulations were performed of releases of magnitudes 500, 1000, 1500 and 2000, beginning at crop ages six, nine, twelve and fifteen months, repeated every seven days. The results of these simulations are compared in Figure 6.11. The results show (1) that starting the releases earlier results in lower percent stalk length bored and (2) that higher magnitudes of parasitoid releases result in marked reductions in the percent stalk length bored.

As mentioned earlier, recommendations on which release strategy is best requires information on the cost of each release. Based on the percent gains in RV per release, it would be recommended that the less frequent releases be adopted.

Chapter 7

Sensitivity analysis

7.1 Introduction

A mathematical model is defined by a series of equations, parameters and variables aimed at characterizing the processes being investigated. Input parameters are subject to many sources of uncertainty including errors of measurement, absence of information and poor or partial understanding of the driving forces and mechanisms (Fürbringer, 1996). In the model developed here, some of the parameter values used are either laboratory values or have been adopted from laboratory values and it is not clear how closely they fit actual field behaviour. In addition, certain aspects of the model rely on output from the CANEGRO model which may also have its own limitations. This imposes a limit on the confidence in the response or output of

the model. The question as to whether the uncertainty in parameter values can lead to a contradiction or invalidation of the model conclusions of the policy analysis or alter model behaviour must thus be investigated.

Frank (1978) identified a number of factors as the cause of discrepancies between the actual system being modeled and the model which very well apply to the system being modeled here. These are:

- System behaviour can change in an unpredictable way due to changes in the condition of the environment under which the system thrives. For example, in the case of *E. saccharina*, changes in sugarcane farming practice could result in a different response in the attack rate of sugarcane by *E. saccharina*.
- In order to make the mathematical model simple and solvable, many aspects of the real system are ignored.
- Exact identification of the system is made difficult by inadequate or inaccurate measuring devices.

Van Coller (1992) added the following factor:

- Lack of complete understanding of the system leads to assumptions being made about the processes which are not completely understood.

One way by which the reliability of the model output can be assessed is by using sensitivity analysis. According to Saltelli et al. (2000a), sensitivity analysis is the study of how the variation in the output of a model can be attributed to different sources of variation. Similarly, Frey et al. (2002) and Marshall (1999) define sensitivity analysis as the assessment of the impact of changes in input values on model outputs. Sensitivity analysis aims to ascertain how the model depends upon the information fed into it. It can be a valuable tool in building confidence in the model and in the embedded computer code (Ascough II et al., 2005).

Saltelli et al. (2000a, 2000b) suggest that sensitivity analysis is a must for model builders and should be conducted in order to determine among various factors

- if a model resembles the system under study;
- the factors that contribute the most to output variability and that require additional research to strengthen the knowledge base;
- the model parameters (or parts of the model itself) that are insignificant, and that can be eliminated from the final model;
- if there is some region in the space of input factors for which the model variation is maximum;
- if (and which) factors interact with each other.

Various methods of sensitivity analysis have been discussed in literature (Ascough II et al., 2005; Frey and Patil, 2002; Ravalico et al., 2005; Saltelli et al., 2000a; Saltelli et al., 2000b). Such methods may be classed as screening, local and global sensitivity analysis methods (Ascough II et al., 2005). Screening methods are used to identify the most sensitive parameters, local methods involve making small perturbations of parameter values around a fixed value while global methods require knowledge of the probability distribution of the parameter values and can give indications of sensitivities to individual parameters while all parameters vary simultaneously. The reason for performing a sensitivity analysis together with the structure of the model determine the method to be used as each method has strengths and limitations regarding the type of insight it can provide (Ascough II et al., 2005; Ravalico et al., 2005)

For the purposes of this study, we wish to determine which parameters contribute the most to output variability. The traditional sensitivity analysis approach (see Tomovic, 1963) which indicates the effect of individual parameter perturbations on model results, will be employed.

7.2 Model sensitivity to changes in *E. saccharina* parameters

In this section, the sensitivity of model output to the various *E. saccharina* parameters is investigated. The procedure involves perturbing the relevant

E. saccharina parameter value by ±10%, while holding all other parameters constant, and noting the percentage change in the percent stalk length bored when compared with the results found using the parameter values given in Chapter 3 as nominal parameter values for a given field and temperature data scenario. The *E. saccharina* parameters are then ranked accordingly. Since *E. saccharina* parameters in the model are stage-specific, the sensitivity analysis was conducted by first grouping the parameters according to type. The types of parameters are mortality rates, threshold temperatures and degree-day ranges for stage development. The moth egg laying rate is also treated as a separate group because this also depends on the age of the moth (in days).

7.2.1 Model sensitivity to stage-specific mortality rates

To test model sensitivity to stage-specific mortality rates, the model was first run with all parameters set at nominal values for a particular field, a particular temperature season and a particular CANEGRO setting for crop condition. The percent stalk length bored was recorded for this run at the key dates of mill closure (November) and mill reopening (March). Each stage-specific mortality rate was then adjusted upward and downward by 10%, one at a time, while all others were kept at their nominal values. The percent stalk length bored was again noted for each of these runs at the same dates of mill closure and reopening used for the nominal run. The percent changes in recorded percent stalk length bored was then noted for each adjustment

in parameter value.

The results of the above simulations are shown in Table 7.1.

Table 7.1: Sensitivity of percent stalk length bored to changes in stage-specific mortality rates of *E. saccharina*.

change in parameter value	minus 10%		plus 10%	
	% change in $\%SLB$		% change in $\%SLB$	
parameter changed	Nov	Mar	Nov	Mar
d_{e} (egg)	7	12	−7	−12
d_{sl} (small larva)	87	179	−87	−179
d_{ll} (large larva)	3	6	−3	−6
d_{p} (pupa)	1	2	−1	−2
d_{m} (moth)	12	29	−12	−29

The results of Table 7.1 gave rise to three important observations: (1) there is a negative relationship between mortality rates and percent stalk length bored (as expected, the higher the mortality rate, the lower the damage), the magnitudes being similar whether the change is upward or downward, (2) the model is highly sensitive to the mortality rate of the stage of small larvae in the *E. saccharina* life cycle, and (3) crop age has an influence on the results of sensitivity analysis as can be seen from the date when the readings were taken (November and March readings). The latter observation suggested that similar analysis needed to be performed for various crop cycles in order to get a clearer picture regarding the effect of crop age. This is crucial because the harvesting decision is based on infestation levels in November and predicted infestation levels for the following March.

In order to address the question posed by the second observation, the analysis was performed for crop cycles whose ages at the November readings were 12 months, 13 months, 14 months, 15 months and 16 months. The results of the analysis are presented in Table 7.2. To give a clearer picture of the results in Table 7.2 a chart of the sensitivity analysis for the more sensitive parameters (d_{sl} and d_{m}) at different crop age is shown in Figure 7.1.

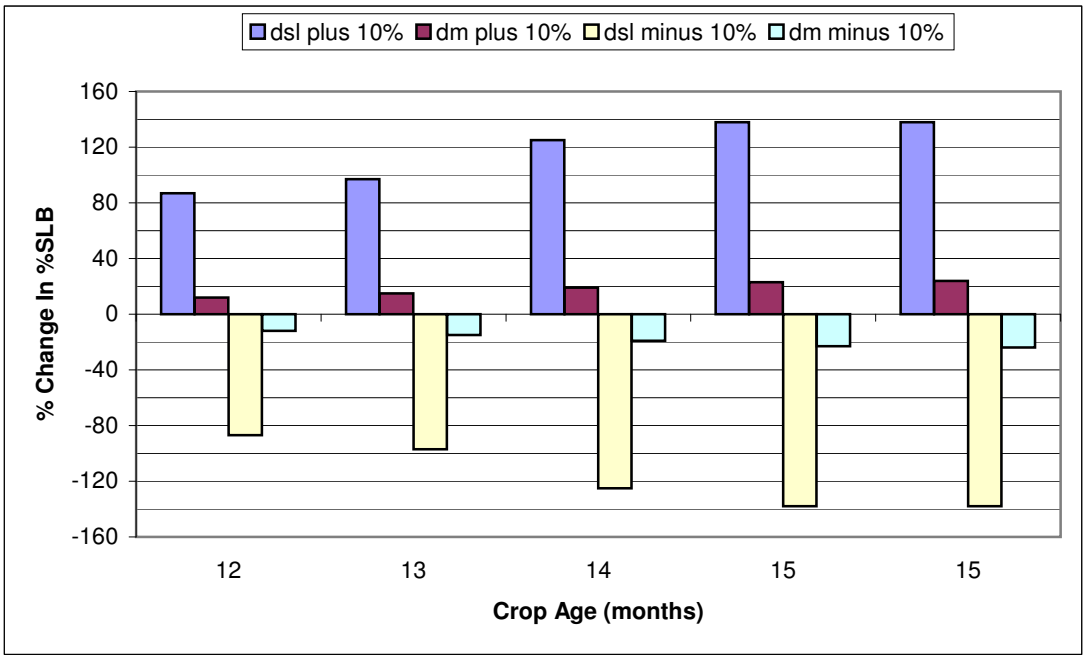

Figure 7.1: The relationship between crop age and the sensitivity of the model to changes in mortality rates of small larvae and moths.

From the results of Table 7.2 and Figure 7.1, it is clear that as the age of the crop increases, the model becomes more sensitive to changes in the mortality rates of small larvae and moths and care should be taken to ensure that these parameters are measured with more accuracy if the model is to be used to simulate *E. saccharina* damage for older crops.

Table 7.2: Sensitivity of percent percent stalk length bored to changes in stage-specific mortality rates of *E. saccharina* for various crop cycles.

change in parameter value		minus 10%		plus 10%	
Crop age (months)	parameter changed	$\%SLB$ change (%)		$\%SLB$ change (%)	
		Nov	Mar	Nov	Mar
12	d_{e}	7	12	−7	−12
	d_{sl}	87	179	−87	−179
	d_{ll}	3	6	−3	−6
	d_{p}	1	2	−1	−2
	d_{m}	12	29	−12	−29
13	d_{e}	8	13	−8	−13
	d_{sl}	97	201	−97	−201
	d_{ll}	4	7	−4	−7
	d_{p}	1	2	−1	−2
	d_{m}	15	34	−15	−34
14	d_{e}	9	15	−9	−15
	d_{sl}	125	245	−124	−245
	d_{ll}	5	8	−5	−8
	d_{p}	1	2	−1	−2
	d_{m}	19	38	−19	−38
15	d_{e}	10	15	−10	−15
	d_{sl}	138	261	−138	−261
	d_{ll}	5	8	−5	−8
	d_{p}	1	2	−1	−2
	d_{m}	23	43	−23	−43
16	d_{e}	10	15	−10	−15
	d_{sl}	138	263	−138	−263
	d_{ll}	5	8	−5	−8
	d_{p}	1	2	−1	−2
	d_{m}	24	44	−24	−44

7.2.2 Model sensitivity to stage-specific temperature thresholds

To test the model sensitivity to temperature thresholds for development of each stage in the *E. saccharina* life cycle, the procedure undertaken was

similar to the one in the preceding section. That is, the model was run for a particular crop cycle with all parameters held at nominal value and then each temperature threshold for development changed by 10%, one at a time, and noting the change in $\%SLB$ at the dates of interest, being November and the following march.

The results of these simulations are shown in Table 7.3.

Table 7.3: Sensitivity of percent percent stalk length bored to changes in stage-specific temperature thresholds for the development of *E. saccharina*.

change in parameter value	minus 10%		plus 10%	
	% change in $\%SLB$		% change in $\%SLB$	
parameter changed	Nov	Mar	Nov	Mar
T_{th}^{e} (egg)	3	5	−3	−5
$T_{\text{th}}^{\text{sl}}$ (small larva)	76	134	−76	−134
$T_{\text{th}}^{\text{ll}}$ (large larva)	48	64	−48	−64
T_{th}^{p} (pupa)	4	6	−4	−6

From the results shown in Table 7.3, it is clear that the model is highly sensitive to changes in threshold temperatures for both larval stages as these give a relatively high change in $\%SLB$ for a relatively low perturbation of the parameter value. As was the case with the mortality rates, there is a negative relationship between changes in threshold temperatures for development and crop damage and the magnitude of change in $\%SLB$ is similar when parameters are perturbed by the same amount up or down. The negative relationship between changes in temperature thresholds and $\%SLB$ is as expected because with lower temperature thresholds, the *E. saccharina* life stages will develop faster and will be more active and hence cause more

damage.

To get a sense of the variations in model sensitivity to parameter changes as the crop ages, the procedure of the preceding sections was repeated for the threshold temperatures. The results of the simulations are shown in Table 7.4 and Figure 7.2.

Table 7.4: Sensitivity of percent percent stalk length bored to changes in stage-specific mortality rates of *E. saccharina* for various crop cycles.

magnitude of change in parameter value		10%	
Crop age (months)	parameter changed	$\%SLB$ change (%)	
		Nov	Mar
12	T_{th}^{e}	3	5
	$T_{\text{th}}^{\text{sl}}$	76	134
	$T_{\text{th}}^{\text{ll}}$	48	64
	T_{th}^{p}	4	6
13	T_{th}^{e}	3	5
	$T_{\text{th}}^{\text{sl}}$	80	154
	$T_{\text{th}}^{\text{ll}}$	48	65
	T_{th}^{p}	5	8
14	T_{th}^{e}	4	6
	$T_{\text{th}}^{\text{sl}}$	106	175
	$T_{\text{th}}^{\text{ll}}$	48	66
	T_{th}^{p}	5	8
15	T_{th}^{e}	4	6
	$T_{\text{th}}^{\text{sl}}$	107	176
	$T_{\text{th}}^{\text{ll}}$	48	67
	T_{th}^{p}	5	8
16	T_{th}^{e}	5	7
	$T_{\text{th}}^{\text{sl}}$	108	201
	$T_{\text{th}}^{\text{ll}}$	49	71
	T_{th}^{p}	7	9

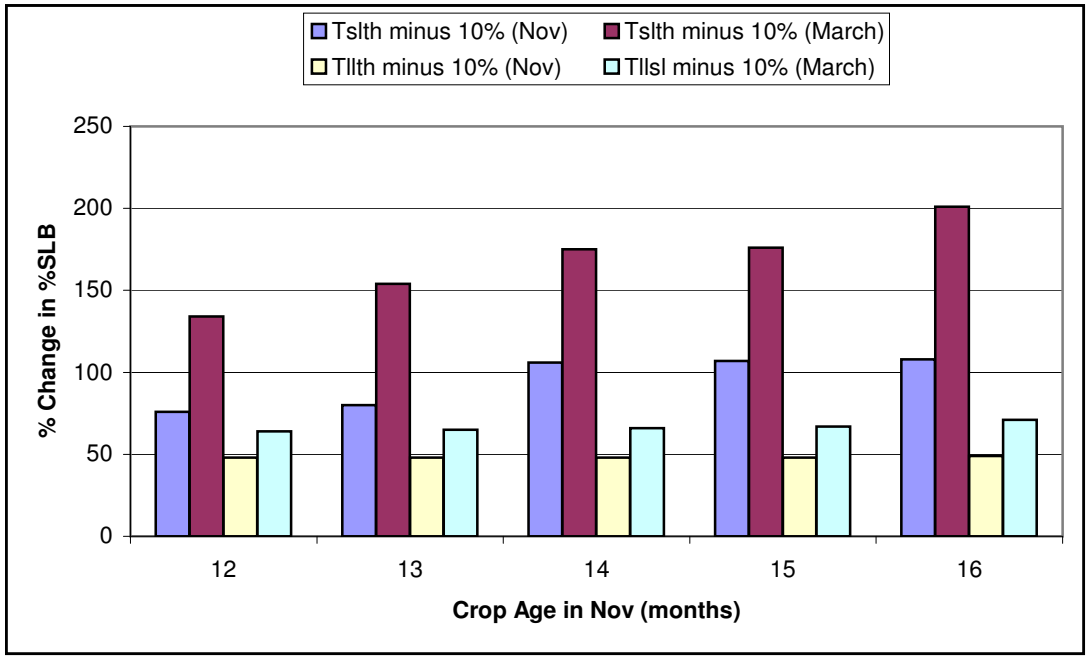

Figure 7.2: The relationship between crop age and the sensitivity of the model to changes in temperature thresholds for development of small larvae and large larvae.

The results in Table 7.4 show that crop age does not affect model sensitivity to changes in temperature thresholds for all the stages except, to a small extent, the small larva stage. It is, however, clear that care should be taken in the measurements of the temperature thresholds for development for both larval stages as the model shows high sensitivities to these parameters.

7.2.3 Model sensitivity to stage-specific degree-day ranges

In this section, the model's sensitivity to the stage-specific degree-day ranges (see Table 3.3 on page 39) is investigated. The procedure was to bring forward or delay the onset of maturation to the next stage by 10%, one stage at a time, while keeping the °C · d ranges for each stage development ($DD_{\max} - DD_{\min}$) the fixed and noting the corresponding change in the percent stalk length bored at the dates of interest (November and March).

The results of the simulation are shown in Table 7.5.

Table 7.5: Sensitivity of percent percent stalk length bored to changes in the onset of maturation from one stage to the next in the development of *E. saccharina*.

change in parameter value	minus 10%		plus 10%	
	% change in $\%SLB$		% change in $\%SLB$	
parameters changed	Nov	Mar	Nov	Mar
$DD^{\mathrm{e}}_{\min}$ & $DD^{\mathrm{e}}_{\max}$ (egg)	8	13	−8	−13
$DD^{\mathrm{sl}}_{\min}$ & $DD^{\mathrm{sl}}_{\max}$ (small larva)	40	63	−40	−63
$DD^{\mathrm{ll}}_{\min}$ & $DD^{\mathrm{ll}}_{\max}$ (large larva)	7	12	−7	−12
$DD^{\mathrm{p}}_{\min}$ & $DD^{\mathrm{p}}_{\max}$ (pupa)	1	2	−1	−2

It is again clear from the results of Table 7.5 that there is a negative relationship between $\%SLB$ and changes in the onset of maturation from one stage to the next. This is as expected because early maturation will give rise to more frequent generations meaning more *E. saccharina* feeding on the crop. Again, the model is found to be most sensitive to parameter changes for the small larval stage. The sooner the small larvae mature into large larvae, a

lot more will escape mortality due to natural predators and hence more large larvae will feed on the sugarcane stalk, thus increasing $\%SLB$.

As in the preceding sections, simulations were performed in order to get a sense of how model sensitivity to degree-day range changes as crop age varies. The results are shown in Table 7.6 and Figure 7.3.

Table 7.6: Sensitivity of percent percent stalk length bored to changes in stage-specific mortality rates of *E. saccharina* for various crop cycles.

magnitude of change in parameter value		10%	
Crop age (months)	parameters changed	$\%SLB$ change (%)	
		Nov	Mar
12	DD^{e}_{min} & DD^{e}_{max}	8	13
	DD^{sl}_{min} & DD^{sl}_{max}	40	63
	DD^{ll}_{min} & DD^{ll}_{max}	7	12
	DD^{p}_{min} & DD^{p}_{max}	1	2
13	DD^{e}_{min} & DD^{e}_{max}	8	16
	DD^{sl}_{min} & DD^{sl}_{max}	47	63
	DD^{ll}_{min} & DD^{ll}_{max}	8	17
	DD^{p}_{min} & DD^{p}_{max}	1	3
14	DD^{e}_{min} & DD^{e}_{max}	11	16
	DD^{sl}_{min} & DD^{sl}_{max}	55	71
	DD^{ll}_{min} & DD^{ll}_{max}	9	22
	DD^{p}_{min} & DD^{p}_{max}	3	4
15	DD^{e}_{min} & DD^{e}_{max}	11	16
	DD^{sl}_{min} & DD^{sl}_{max}	58	71
	DD^{ll}_{min} & DD^{ll}_{max}	10	34
	DD^{p}_{min} & DD^{p}_{max}	5	6
16	DD^{e}_{min} & DD^{e}_{max}	13	18
	DD^{sl}_{min} & DD^{sl}_{max}	58	75
	DD^{ll}_{min} & DD^{ll}_{max}	14	35
	DD^{p}_{min} & DD^{p}_{max}	6	9

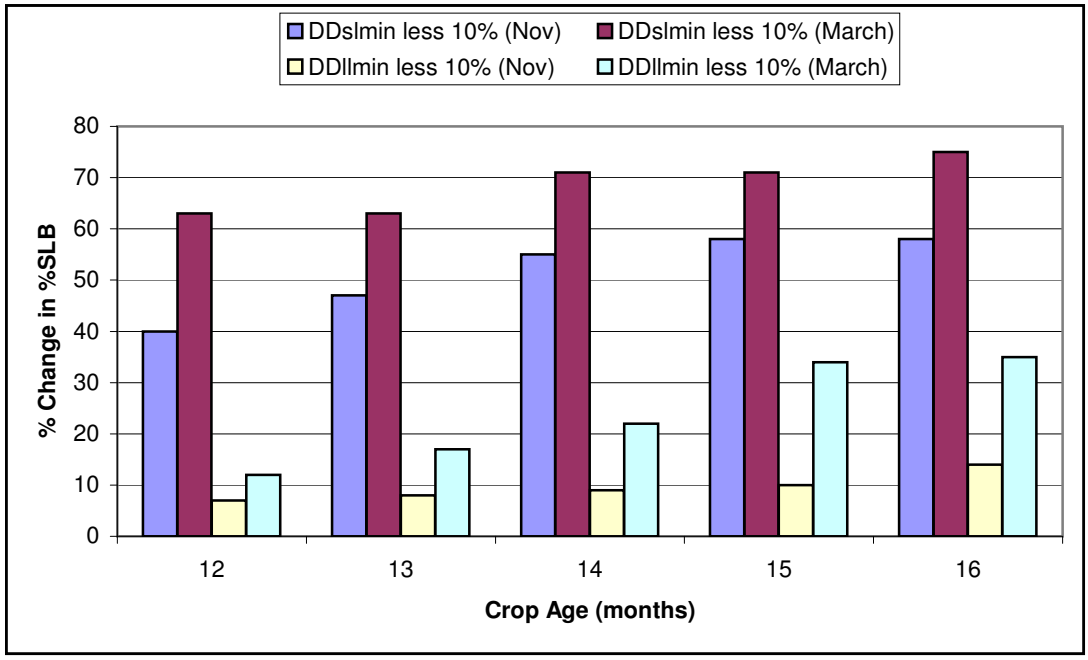

Figure 7.3: The relationship between crop age and the sensitivity of the model to changes in the onset of maturation from one stage to another for the small larva and large larva stages.

From the results of Table 7.6 and Figure 7.3 it can be concluded that the model output is highly sensitive to changes in the onset of maturation from small larvae to large larva and that crop age can increase the sensitivity for all the other stages.

7.2.4 Model sensitivity to moth-age-specific egg-laying rate

In this section, the model sensitivity to changes in the number of eggs laid per female moth based on the number of days lived by the moth, $ELR(n)$, (see equation 3.13 on page 41 and Table 3.7 on page 51) is investigated.

The procedure was to set all parameters to their nominal values and then perturbing, by 10%, the number of eggs laid per female moth at the various moth ages, one at a time, and then noting the corresponding change in the percent stalk length bored at the key dates of November and March.

The results of these simulations are shown in Table 7.7.

Table 7.7: Sensitivity of percent percent stalk length bored to a 10% increase in the *E. saccharina* moth egg laying rate $ELR(n)$ based on moth age (n).

Moth age (days)		1	2	3	4	5
Change in	Nov	2	3	2	1	6
$\%SLB$ (%)	Mar	4	6	4	3	10

Table 7.7 indicates that the change in $\%SLB$ is directly proportional to the change in the moth egg laying rate. This is as expected as more *E. saccharina* larvae will be in the system if more eggs are laid. The results also suggest that $\%SLB$ is not sensitive to changes in the moth egg laying as the change in percent stalk length bored is within the 10% at which moth egg laying rates were adjusted. Of course, this has to be confirmed by performing similar

analysis for older crops.

The results of testing the model sensitivity to changes in *E. saccharina* moth egg laying rates as crop age varies are shown in Table 7.8 and Figure 7.4.

Table 7.8: Sensitivity of percent percent stalk length bored to a 10% increase in the *E. saccharina* moth egg laying rate based on moth age as a function of crop age.

	moth age (days)	crop age (months)				
		12	13	14	15	16
% change in $\%SLB$ in Nov	1	2	2	3	3	3
	2	3	3	5	5	5
	3	2	2	3	3	3
	4	1	2	2	2	2
	5	6	7	8	8	9
% change in $\%SLB$ in Mar	1	4	4	5	5	5
	2	6	7	9	9	9
	3	4	4	5	5	5
	4	3	3	4	4	4
	5	10	12	12	14	14

The results shown in Figure 7.4 and Table 7.8 suggest that even as the crop gets older, the model output has low sensitivity to changes in the age-specific egg laying rates of *E. saccharina* moths.

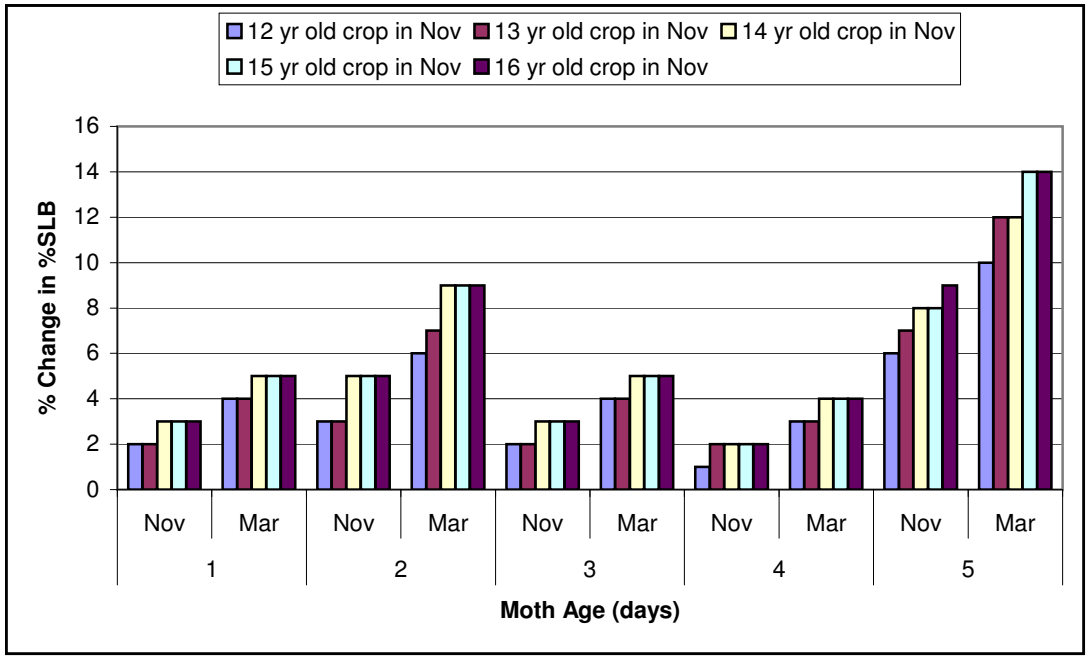

Figure 7.4: The relationship between crop age and the sensitivity of the model to changes in the age-specific egg laying rates of *E. saccharina* moths.

7.2.5 Overall *E. saccharina* parameter sensitivity ranking

The *E. saccharina* parameters were ranked according to the highest percentage change of $\%SLB$ achieved for a 10% change in the parameter value when all cases are considered, including crop age. Only those parameters that caused a more than 10% change in $\%SLB$ were ranked. Using these criteria, the ranking is given in Table 7.9.

Table 7.9: Ranking of *E. saccharina* parameters according to how a 10% change in parameter value affects percent stalk length bored. The most sensitive parameter is ranked first. Parameters that gave a less than 10% change in percent stalk length bored are not ranked.

Parameter	Description	Rank
d_{sl}	small larva mortality rate	1
$T_{\mathrm{th}}^{\mathrm{sl}}$	small larva threshold temperature	2
$T_{\mathrm{th}}^{\mathrm{ll}}$	large larva threshold temperature	3
$DD_{\mathrm{min}}^{\mathrm{sl}} - DD_{\mathrm{max}}^{\mathrm{sl}}$	onset of maturation from small larvae to large larvae	4
$DD_{\mathrm{min}}^{\mathrm{ll}} - DD_{\mathrm{max}}^{\mathrm{ll}}$	onset of maturation from large larvae to pupae	5
d_{m}	moth mortality rate	6
$DD_{\mathrm{min}}^{\mathrm{e}} - DD_{\mathrm{max}}^{\mathrm{e}}$	onset of maturation from eggs to small larvae	7
$ELR(5)$	egg laying rate for moths aged 5 days	8
d_{e}	egg mortality rate	9

7.3 Model sensitivity to number of eggs used in model initialization

The number of eggs used to initialize the model as soon as CANEGRO indicates the presence of dead leaf matter in the crop, EGG_{ini}, is shown in section 3.5 (see Table 3.5 on page 51). Since it is not known what happens in actual field conditions in as far as how *E. saccharina* invades a field, it is necessary to determine how sensitive the model is to changes in these numbers. In order to achieve this, the value of EGG_{ini} for each month was varied by 10%, one at a time, and the corresponding change in percent stalk length bored was noted at the dates of interest (November and March).

It was found that the model showed very little sensitivities to these changes, if

at all. This also proved true for older crop cycles. It was therefore concluded that the model is not sensitive to changes in EGG_{ini}.

7.4 Model sensitivity to changes in *S. parasitica* parameters

In this section, the sensitivity of the biological control model presented in Chapter 4 to changes in *S. parasitica* parameters is investigated. As was done for *E. saccharina* parameters, the *S. parasitica* parameters were first grouped according to type. The group types considered were mortality rates, degree-day ranges for each life stage, threshold temperatures for development and egg laying rates per adult *S. parasitica* fly.

7.4.1 Sensitivity to changes in *S. parasitica* stage-specific mortality rates

In order to test model sensitivity to changes in stage-specific mortality rates of *S. parasitica*, the model was run with all parameters set at their nominal rates using a release strategy of once every seven days (to coincide with release strategies currently under investigation (Conlong, pers. comm.)). A reading of percent stalk length damaged was taken at the end of the simulation. The relevant stage-specific mortality rates were then varied by 10%, one at a time, and the corresponding change in percent stalk length bored at the end of the

simulation noted. The results of the simulations are given in Table 7.10.

Table 7.10: Sensitivity of percent percent stalk length bored to changes in stage-specific mortality rates of *S. parasitica*.

change in parameter value	minus 10%	plus 10%
parameter changed	% change in $\%SLB$	% change in $\%SLB$
d_{mg} (maggot)	-0.05	0.05
d_{spp} (pupa)	-0.05	0.05
d_{fly} (fly)	-0.5	0.5

It is clear from Table 7.10 that the biological control model is not sensitive to changes in the stage-specific mortality rates of *S. parasitica* since a 10% change in parameter value results in very little or no change in the percent stalk length recorded at the end of the simulation. It is also interesting to note that percent change in $\%SLB$ is directly proportional to change in mortality rate of *S. parasitica*. This is expected since a drop in *S. parasitica* mortalities would result in more *S. parasitica* survivors to attack *E. saccharina* and hence a reduction in the percent stalk length bored.

7.4.2 Sensitivity to stage-specific *S. parasitica* threshold temperatures

To determine model sensitivity to stage-specific *S. parasitica* threshold temperatures for development, threshold temperatures for maggots and pupae were perturbed by 10% one at a time and the changes in percent stalk length bored at the end of the simulation were noted.

The results of the above analysis are shown in Table 7.11.

Table 7.11: Sensitivity of percent percent stalk length bored to changes in stage-specific temperature thresholds for *S. parasitica* development.

change in parameter value	minus 10%	plus 10%
parameter changed	% change in $\%SLB$	% change in $\%SLB$
$T_{\text{th}}^{\text{mg}}$ (maggot)	−0.06	0.06
$T_{\text{th}}^{\text{spp}}$ (pupa)	−1.76	1.76

It is again clear from Table 7.11 that the model is not sensitive to changes in *S. parasitica* threshold temperatures for development. The apparent direct proportionality relationship between changes in threshold temperatures and changes in percent stalk length bored is because reduced threshold temperatures translate to a faster rate of development of *S. parasitica* stages which will in turn result in more attacks on *E. saccharina*, thus reducing the percent stalk length bored.

7.4.3 Sensitivity to changes in degree-day ranges for *S. parasitica* life stages

In order to investigate model sensitivity to changes in degree-day ranges for *S. parasitica* life stages, a similar procedure to that which was carried out to investigate model sensitivity to changes in degree-day ranges for *E. saccharina* life stages was followed. The onset of maturation from one stage to the next (DD_{min}) was either brought forward by 10% or brought back by 10% and changing DD_{max} in such a way that $DD_{\text{max}} - DD_{\text{min}}$ remained the

same as for nominal values.

The results of the above analysis are shown in Table 7.12.

Table 7.12: Sensitivity of percent percent stalk length bored to changes in the onset of maturation from one stage to the next in the *S. parasitica* life cycle.

change in parameter value	minus 10%	plus 10%
parameter changed	% change in $\%SLB$	% change in $\%SLB$
$DD_{\min}^{\text{mg}}$ & $DD_{\max}^{\text{mg}}$ (maggot)	-0.06	0.06
$DD_{\min}^{\text{spp}}$ & $DD_{\max}^{\text{spp}}$ (pupa)	-1.76	1.76

The results of Table 7.12 show that the model is not sensitive to changes in the onset of maturation from one stage to another.

Simulations were also performed in order to determine the sensitivity of the model to changes in the length of the period $DD_{\min}$ to $DD_{\max}$ and similar results were obtained. That is, the model was found not to be sensitive to changes in the length of the period $DD_{\min}$ to $DD_{\max}$.

7.4.4 Sensitivity to age-specific maggot laying rate of *S. parasitica* flies

The procedure here was similar to the procedure for testing model sensitivity to age-specific egg laying rates for *E. saccharina* moths. That is, the maggot laying rate for flies of different ages were varied by 10%, one at a time and

the percent stalk length bored recorded was compared to that found from using nominal values.

As seems to be the trend with *S. parasitica* parameters, it was found that the model is not sensitive to changes in the age-specific maggot laying rate for flies. The little change that was recorded showed an inverse proportionality relationship between changes in age-specific maggot laying rates and percent stalk length bored by *E. saccharina* larvae (see Table 7.13). This is again as expected since increasing the maggot laying rate will increase the chances of *E. saccharina* larvae being attacked, and hence percent stalk length bored will be lower.

Table 7.13: Sensitivity of percent percent stalk length bored to changes in age-specific maggot laying rate of *S. parasitica* flies.

	change in egg laying rate	
	minus 10%	plus 10%
fly age (days)	% change in $\%SLB$	% change in $\%SLB$
8	0.06	−0.06
9	0.06	−0.06
10	0.06	−0.06
11	0.11	−0.11
12	0.10	−0.10
13	0.12	−0.12
14	0.12	−0.12

S. parasitica parameters will not be ranked as the model did not display much sensitivity relative to 10% changes in any of them. A worst case scenario where all parameters were changed upwards or downwards by 10% all at once did not show much change to the above as only a 6% change in percent

stalk length bored was recorded.

7.5 Biological control model sensitivity to specific parasitism rate

The specific parasitism rate (SPR) given in equation 4.8 on page 69 is not easily measurable and so model sensitivity to changes in this rate need to be investigated.

In order to test model sensitivity to changes in SPR, the value used in the policy analysis was varied by 10% and the corresponding changes in percent stalk length bored noted.

The simulations showed that the model is not sensitive to changes in SPR as only a 0.1% change in percent stalk length bored was recorded for a 10% change in SPR.

As expected, an increase in SPR resulted in a decrease in percent stalk length bored and a decrease in SPR resulted in an increase in percent stalk length bored.

7.6 Insecticide parameters

The insecticide kill rates used in the policy analysis in section 6.3 are all assumed values. Model sensitivity to these rates therefore needs to be investigated.

Again, the procedure was to vary each insecticide kill rate by 10%, one at a time, and noting the change in percent stalk bored that results. The results of these simulations are shown in Table 7.14. The last row of Table 7.14 indicates what happened when all kill rates were adjusted 10% upwards. It is clear that the model is not sensitive to changes in insecticide kill rate. The negative numbers indicate, as expected, that the higher the insecticide kill rate, the lower the percent stalk length bored by *E. saccharina* larvae.

Table 7.14: Sensitivity of percent percent stalk length bored to 10% changes in insecticide kill rate for various *E. saccharina* larval instars.

larval instar	% change in $\%SLB$
1	-1.6
2	-1.2
3	-1.4
All	-3.0

7.7 Multiplier function parameters

In this section, model sensitivity to changes in the parameters of the multiplier functions used in the model is investigated. The multiplier functions to be investigated are the stress multiplier function (g_{stress}, shown in Figure 3.3 and discussed in Appendix A.3), the quality of life multiplier function (g_{ind}, shown in Figure 3.4 and Figure A.3) and the density dependent functions f_L (shown in Figure 4.2(a) and Figure A.1) and f_M (shown in Figure 4.2(b) and Figure A.2) used in the biological control model.

Each multiplier function is treated separately in the sections that follow.

7.7.1 Model sensitivity to changes in stress multiplier function (g_{stress}) parameters

The stress multiplier function given by equation A.4 in Appendix A.3 has the parameters denoted by h, A and B. To test model sensitivity to changes in these parameters, the parameters were adjusted upwards and downwards by 10% and the changes in percent stalk length bored were noted. The results of the simulation are shown in Table 7.15

The results of Table 7.15 show that the model is not sensitive to changes in the parameter h (determining the slope of g_{stress}) of the stress multiplier

Table 7.15: Sensitivity of percent percent stalk length bored to changes in stress multiplier function parameters. The row labeled "All" refers to a worst case scenario where all parameters are adjusted in the same direction at the same time.

change in parameter value	minus 10%		plus 10%	
	% change in $\%SLB$		% change in $\%SLB$	
parameter changed	Nov	Mar	Nov	Mar
h	−3.4	−5.0	3.4	5.0
A	−17	−24	17	24
B	−12	−17	12	17
All	−33	−48	33	48

function and is more sensitive to the parameters A and B [which determine the upper bound (to some extent for A) and lower bound B of the multiplier function].

7.7.2 Model sensitivity to the "quality of life" index multiplier function, g_{ind}

The "quality of life" index multiplier function g_{ind} given by equation A.5 in Appendix A.4 has the parameters m and K. To test model sensitivity to changes in these parameters, the parameters were adjusted upwards and downwards by 10% and the changes in percent stalk length bored were noted. The results of the simulation are shown in Table 7.16

The results of Table 7.16 show that the model is sensitive to changes in the parameter K in the "quality of life" index multiplier function and not

Table 7.16: Sensitivity of percent percent stalk length bored to changes in the "quality of life" index multiplier function parameters. The row labeled "All" refers to the scenario where all parameters were adjusted in the same direction at the same time.

change in parameter value	minus 10%		plus 10%	
	% change in $\%SLB$		% change in $\%SLB$	
parameter changed	Nov	Mar	Nov	Mar
K	-23	-38	23	38
m	3	4	-3	-4
All	-20	-34	20	34

sensitive to the parameter m.

7.7.3 Biological control model sensitivity to the density dependent functions f_L and f_M

The density dependent functions f_L and f_M given respectively by equation A.2 in Appendix A.1 and equation A.3 in Appendix A.2 each have parameters represented by m an K.

To test the model sensitivity to changes in the parameters of these functions, the parameters were adjusted upwards and downwards by 10%, one at a time, and the change in percent stalk length bored at the end of the simulation was noted.

The results of the sensitivity analysis showed that the model is not sensitive

to changes in any of the parameters in both density dependent functions since in all cases, a 10% change in parameter value gave no more than a 0.5% change in percent stalk length bored. Even in the worst case scenarios of adjusting all the parameters at the same time such that in each case, the net effect was to increase (or decrease) the percent stalk length bored, it was found that the net effect of the combined changes produced a less than 0.5% change in percent stalk length bored.

7.8 Overall ranking of parameters

In this section all the parameters considered in the preceding sections are ranked from highest to lowest based on by how much a 10% change in the parameter changed the percent stalk length bored. Parameters that showed a less than 10% change in percent stalk length were considered to produce no sensitivity in the model and are therefore not ranked.

The ranked parameters are shown in Table 7.17. In Table 7.17, a positive direction of change means that an increase/decrease in parameter value resulted in an increase/decrease, respectively, in percent stalk length bored while a negative direction of change means an increase/decrease in a decrease/increase respectively, in percent stalk length bored.

It is recommended that before any of the policy analysis results are imple-

Table 7.17: Ranking of model parameters according to how a 10% change in parameter value affects percent stalk length bored. The most sensitive parameter is ranked first. Parameters that gave a less than 10% change in percent stalk length bored are not ranked.

Rank	Parameter	Direction of change
1	d_{sl}	$-$
2	$T_{\mathrm{th}}^{\mathrm{sl}}$	$-$
3	$T_{\mathrm{th}}^{\mathrm{ll}}$	$-$
4	$DD_{\mathrm{min}}^{\mathrm{sl}} - DD_{\mathrm{max}}^{\mathrm{sl}}$	$-$
5	K in g_{ind}	$+$
6	A in g_{stress}	$+$
7	B in g_{stress}	$+$
8	$DD_{\mathrm{min}}^{\mathrm{ll}} - DD_{\mathrm{max}}^{\mathrm{ll}}$	$-$
9	d_{m}	$-$
10	$DD_{\mathrm{min}}^{\mathrm{e}} - DD_{\mathrm{max}}^{\mathrm{e}}$	$-$
11	$ELR(5)$	$+$
12	d_{e}	$-$

mented, great care should be taken in measuring these parameters as errors in these will greatly affect the outcome of the results. Moreover, their combined effect has not been investigated and there is a possibility that a combination of wrongly specified parameters from Table 7.17 could could result in greatly exaggerated conclusions.

Chapter 8

Spatial considerations

8.1 Introduction

The *E. saccharina* model presented in the previous chapters does not explicitly model the possible migration of the pest from one field to the next. In the model it is assumed that moths "from somewhere" will attack a mature field. Once a field has established its own moths, future *E. saccharina* generations are determined by what is available within the field. The question that needs to be asked, therefore, is: *What effect on each other's infestation levels would adjacent fields have?*

Whilst the *E. saccharina* moth does not fly too far (Atkinson and Carnegie, 1989), the possibility of an adjacent mature field infecting a young field is,

however, real – a gust of wind in the right direction making it possible. In the model, it is assumed that a sugarcane field will get attacked by *E. saccharina* as soon as the field is mature enough to produce dead leaf matter, as this is the preferred oviposition site of the pest (Conlong and Hastings, 1984; Leslie, 1990), and this is modeled by a certain number of eggs assumed to be laid per day. Of course female moths need to be available for this to occur. In this chapter, certain scenarios that can make this possible are investigated.

Three possibilities can occur: (1) The field under consideration may be adjacent to a wetland sedge which is the natural host for *E. saccharina* (Girling, 1972; Atkinson, 1979; Atkinson, 1980; Conlong, 1994b). (2) The field may be adjacent to a mature field already infested with *E. saccharina*. (3) Infestation may come from infected sugarcane being transported to the mill when pupae in that crop mature to moths which then fly off onto a susceptible field near the road.

The situations described in (1) – (3) are illustrated in Figure 8.1. In the investigations that follow, it will be assumed that each field has uniform *E. saccharina* density and hence the fields themselves will not be compartmentalized. As before, each field block simulated will be 1 ha in size and containing 100 000 sugarcane stalks.

Scenarios to be investigated will include the effect of having different varieties (of varying susceptibility to attack by *E. saccharina*) in fields adjacent to each other and how the ages of the adjacent fields affect *E. saccharina* damage

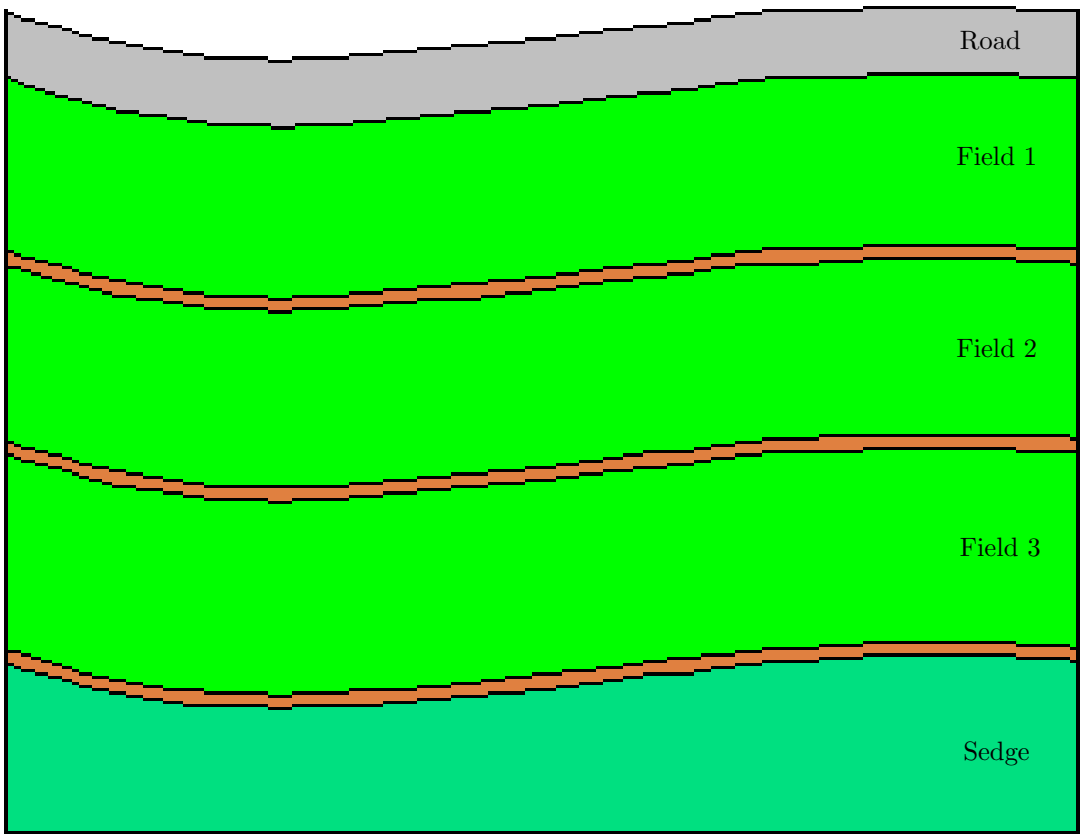

Figure 8.1: Illustration of a layout of sugarcane fields of possibly different ages and varieties, separated by gaps (shown in brown). (Gaps may be used by farmers to access the various field blocks.)

levels.

As this is an illustrative study, the main focus will be to determine what, if any, the effect of dispersal of *E. saccharina* moths is when compared to running the model one field at a time with no interaction between fields.

The approach taken was as follows. The *E. saccharina* spatial model was run for a field initialized as before (assuming it somehow got infected) with adjacent fields assumed to be empty. Simulations for other fields were started at certain time intervals after this and their infestations were linked to the populations in the fields adjacent to them with moths being allowed to move back and forth between fields. The rate of movement from one field to the next depends on the ages of the fields involved, the variety of the crop planted on those fields and moth densities on the fields.

We begin by presenting the *E. saccharina* spatial model set-up.

8.2 The Spatial Model

As stated above, the aim is to investigate the effect of neighbouring fields on the *E. saccharina* population dynamics on particular fields. In this regard, the fields themselves will not be compartmentalized and the only flow of

information will be between neighbouring fields.

The spatial model was designed to simulate the scenario shown in Figure 8.1. In this regard, the approach was to have CANEGRO and the *E. saccharina* model running for each field separately whilst simulating moth migrations between the fields as shown in Figure 8.2.

In order to accommodate the scenarios depicted in Figure 8.2, the *E. saccharina* model presented in Chapter 3 had to be modified for each field.

In keeping with the notation introduced in Chapter 3, let $MTH^{p}_{i,j,k}(t)$ be the number on day t of field p moths ($p = 1, 2, 3$)[1] in the moth cohort that began on day k from $PP^{p}_{i,j}(k)$, where again the superscript p stands for the field number.

Similarly, let $EGG^{p}_{i}(t)$ be the number on day t of field p eggs ($p = 1, 2, 3$) in the egg cohort that began on day i.

Also, let $MTH^{pq}_{i,j,k}(t)$ be the number on day t of those members of $MTH^{p}_{i,j,k}(t)$ that migrate to field q and let $EGG^{pq}_{t}(t)$ be the number of eggs coming from moths migrating from field p to field q on day t. The total number of moths

[1] This notation and what follows can be easily extended to any number of fields under consideration. Computing power available may impose a limit on the number of field situations to be simulated.

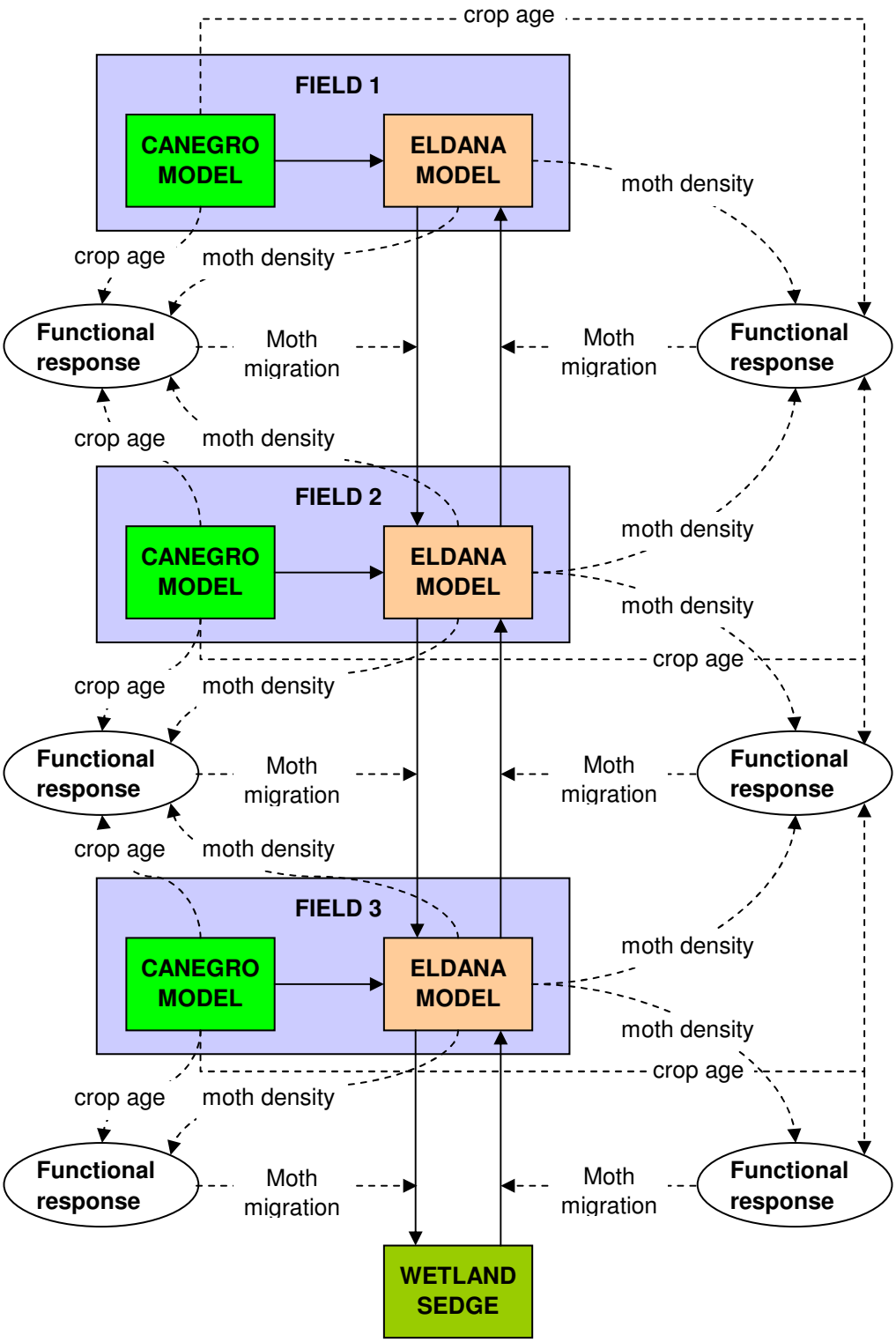

Figure 8.2: The spatial model interaction between fields.

moving from field p to field q on day t is then given by

$$MTH^{pq}(t) = \sum_{i,j,k} MTH^{pq}_{i,j,k}(t), \tag{8.1}$$

so that the total number of moths on field p on day t of the simulation is given by

$$MTH^{p}(t) = \sum_{q} MTH^{qp}(t) + \sum_{i,j,k} MTH^{p}_{i,j,k}(t) - \sum_{q} MTH^{pq}(t), \tag{8.2}$$

where the first sum is taken over all fields q contributing moths to field p, the second sum is over all moth cohorts already present in field p and the third sum is taken over all fields q to which field p contributes moths.

We need to calculate $MTH^{pq}_{i,j,k}(t)$.

Let $MIGF^{pq}$ be the rate at which moths would migrate from field p to field q when all field parameters, i.e., CANEGRO outputs for both fields p and q, are considered equal and when no wind is present. In order to accommodate different field conditions, the number of moths migrating from the cohort $MTH^{p}_{i,j,k}$ in field p to field q is modeled by

$$MTH^{pq}_{i,j,k}(t) = MTH^{p}_{i,j,k}(t) \times MIGF^{pq} \times MIGMULT(\text{age}(p), \rho(p), \text{age}(q), \rho(q)) \tag{8.3}$$

where $MIGMULT$ is a migration multiplier function which takes into consideration the effects on $MIGF^{pq}$ of the relative ages of fields p and q, since *E. saccharina* prefers mature sugar cane (Nuss et al., 1986), and the resis-

tance ratings ρ of the crop on the fields, since certain crop varieties are more resistant to *E. saccharina* (Keeping et al., 2003; Nuss et al., 1986).

In order to simplify $MIGMULT$, it was modeled as the product of two functions. The first function is a function of the relative age [age(p)/age(q)] and is such that it takes on the value 1 when [age(p)/age(q)] = 1, a value larger than 1 when [age(p)/age(q)] < 1 and a value smaller than 1 when [age(p)/age(q)] $>$ 1. A function with such properties is given in Appendix A.2.

The second function in $MIGMULT$ is a function of the relative resistance rating $[\rho(p)/\rho(q)]$. Bearing in mind that the higher the resistance rating index ρ, the more susceptible the crop is to *E. saccharina* attack, the function is such that it takes on the value 1 when $[\rho(p)/\rho(q)] = 1$, a value smaller than 1 when $[\rho(p)/\rho(q)] > 1$ and a value larger than 1 when $[\rho(p)/\rho(q)] < 1$. For example, if $\rho(q) < \rho(p)$, i.e., when field q is more resistant to *E. saccharina* attack than field p, there will be less migration from field p to field q. Again, a function of the form given in Appendix A.2 is used to model this.

The total number of *E. saccharina* eggs coming from moths migrating from field p to field q on day t is then given by

$$EGG_t^{pq} = \sum_{i,j,k} O_{i,j,k}(t) \times MTH_{i,j,k}^{pq}(t) \tag{8.4}$$

where the sum is taken over all members from moth cohorts migrating from field p to field q on day t and where $O_{i,j,k}(t)$ is the moth oviposition rate

defined in equation 3.14. New egg cohorts on day t for field p are given by

$$EGG_t^p(t) = \sum_q EGG_t^{qp}(t) - \sum_q EGG_t^{pq}(t) + \sum_{i,j,k} O_{i,j,k}(t) \times MTH_{i,j,k}^p(t) \quad (8.5)$$

where the first sum in equation 8.5 is taken over all fields q from which moths have migrated to field p; the second sum is taken over all fields q to which moths from field p have migrated; and the third sum is taken over all remaining moth cohorts in field p.

The equations modeling the day-to-day dynamics of $EGG_i^p(t)$, $SLV_i^p(t)$, $LLV_i^p(t)$, $PP_{i,j}^p(t)$ are similar to the ones given in equation 3.1. The equations for the moth cohorts are modified to include migration as follows

$$MTH_{i,j,k}^p(t+1) = MTH_{i,j,k}^p(t) \times \left(1 - M_{i,j,k}^d(t)\right) - \sum_q MTH_{i,j,k}^{pq}(t) \quad (8.6)$$

Note that $MTH_{i,j,k}^{pq}$ takes with it all the cohort information from its parent moth cohort $MTH_{i,j,k}^p$ to the field q where it will lay its eggs. In field q, it is treated as one of field q's moth cohorts and its daily dynamics on field q will be governed by an equation similar to equation 8.6

The above modifications were implemented in programs designed to simulate the different field blocks as illustrated in Figure 8.2.

8.3 Model implementation

In the model of Figure 8.2, field 1 stands for the field used in the initialization process. That is, to get the model going, field 1 starts out under the same assumptions as before where moths are assumed to come from 'somewhere' and lay their eggs as soon as dead leaf matter first appears on the field. Recall that in the model developed in Chapter 3, this 'initialization process' is allowed to run only until the field generates its own *E. saccharina* moth population. After that, future *E. saccharina* generations come from the populations that already exist in the system with no immigration or emigration considered.

In order to implement the spatial model described above to the scenario of Figure 8.1, the model for field 1 is first allowed to run under the 'initialization process' so as to establish an *E. saccharina* population on it. The models for fields 2 and 3 are run concurrently, but without the initialization process. Field 2 then feeds off field 1 moths to get an *E. saccharina* population going on it. By this time, field 1 has begun generating its own *E. saccharina* population and the initialization has stopped, so that in the next crop cycle, field 1 gets attacked by moths from field 2 according to the spatial model modifications given above (as opposed to the assumption that moths come from 'somewhere' as used in the initialization process).

Depending on the status of field 3, moths from field 2 will migrate to field 3

to establish a pest population on it. Once this happens, field 2 will also have some moths coming in from field 3, depending on the field conditions. Field 3 may also lose some moths to the wetland sedge nearby (see Figure 8.2) as sedges attract more moths than sugar cane fields (Conlong, pers. comm.).

Eventually, under the right conditions, the scenario of Figure 8.1 will be able to maintain its own *E. saccharina* populations for each of the three fields.

In the next two sections, the model is used to illustrate the effect of field variety and crop age on the interactions between fields 1, 2 and 3 in the scenario of Figure 8.1. The interactions are illustrated using the crop damage index.

8.4 Crop Variety

8.4.1 Fields of the same crop variety

As a starting point, fields of crop of the same variety were investigated. The variety chosen was NCo376 (with intermediate resistance to *E. saccharina* attacks). This serves to give a benchmark to be used to compare the effects of varying crop varieties on the different field blocks as well as to test the

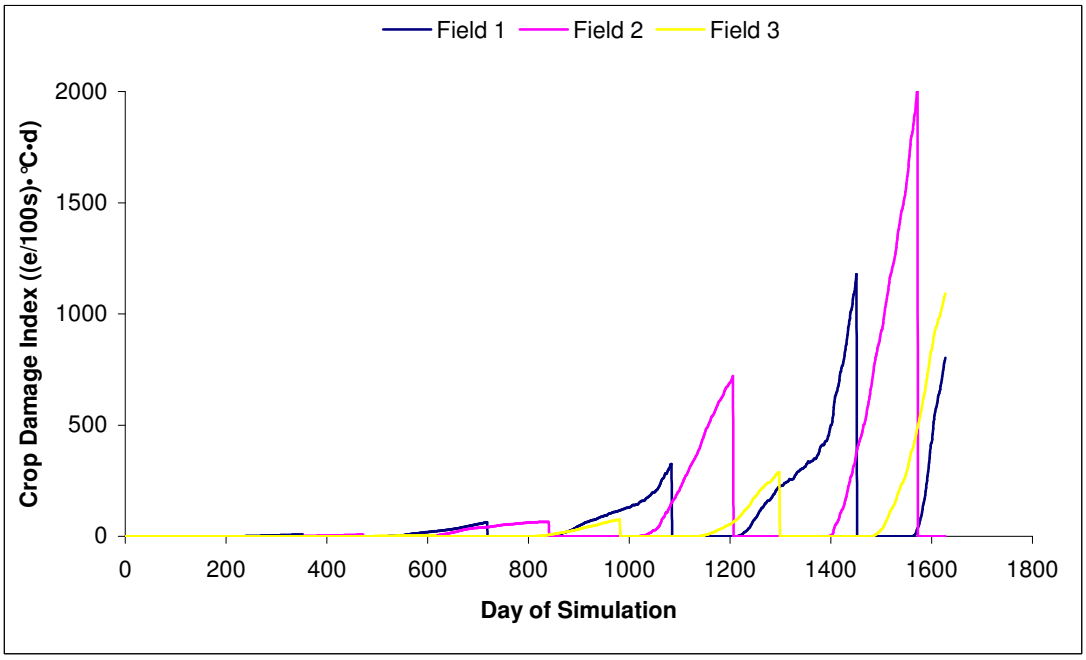

Figure 8.3: Spatial model output showing the damage index for each field when crop of the same variety is considered.

model program.

To achieve this, the spatial model was run such that the crop cycles for each field ran for 12 months, with the crop cycles for field 2 beginning three months after those of field 1 and those of field 3 beginning a further three months later. This was in order to allow sufficient time for the 'initialization process' for field 1 to take effect. The model was run for a total of 5 seasons.

Figure 8.3 shows the damage indices calculated by the model for each of the field blocks over the five seasons.

The results of Figure 8.3 indicate the possible infestation of one field by another whenever the crop cycles of adjacent fields overlap. Taking a closer look at the results of Figure 8.3, it can be concluded that if the crop cycles are maintained this way for long periods with no intervention, the *E. saccharina* infestation levels will continue to grow as the years go by. In fact, when the model was run with the middle field fallowed just for one of the cycles, infestation levels dropped back to zero for the next crop cycles of fields 1 and 3.

8.4.2 Fields of different crop varieties

In order to investigate the effect of crop variety on the infestation levels of neighbouring fields, the model was run with fields 1 and 3 with the same crop varieties as for the simulation of Figure 8.3, whilst field 2 was run with a crop variety more resistant to *E. saccharina* attack. Again, this was done over five crop cycles. Figure 8.4 (a) shows the results of the simulation run.

When comparing the results of Figure 8.4 (a) with those of Figure 8.3 it is clear that by changing the crop variety in one field, marked reductions in the crop damage index can be achieved. That is, by planting crops of higher resistance to *E. saccharina* attack in fields lying between crops of higher susceptibility, infestation levels can be brought down among these fields. Similar results of reduced crop damage index were obtained when all

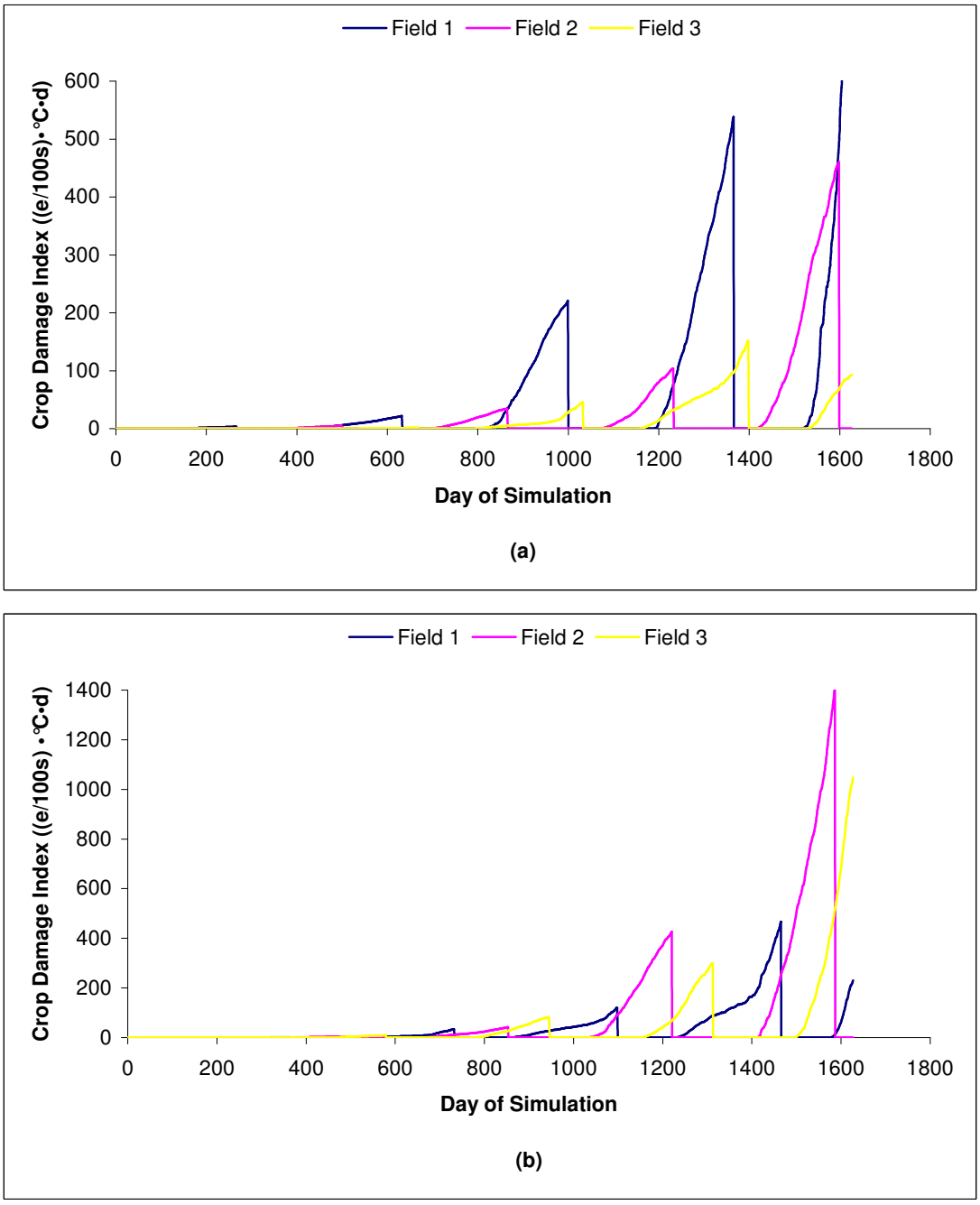

Figure 8.4: (a) Spatial model output showing the damage index for each field when field 2 crop is less susceptible to *E. saccharina* attack than field 1 and field 3 crops. (b) Spatial model output showing the damage index for each field when field 1 crop variety is more susceptible to *E. saccharina* attack than field 2 crop variety which in turn is less susceptible to and field 3 crop variety

three fields had crop varieties of different susceptibility to *E. saccharina* (see Figure 8.4 (b)).

Thus, the above simulation results suggest that farming strategies should involve ensuring that crop varieties with high resistance to *E. saccharina* attack are planted between fields that are more susceptible to attack in order to reduce higher incidents of attack in future ratoon crops.

8.5 Different crop cycle lengths

In order to investigate the impact, if any, of the age of crops in adjacent fields, the model was run for all fields with crop of the same variety, but with crop cycle lengths varying from one harvest to the next. As this is an illustrative study, the lengths of crop cycles for each field were taken at random. For the results presented in this section, the cycle lengths for each field are given in Table 8.1.

The results of the model simulation are shown in Figure 8.5. The results of Figure 8.5 show that when certain fields are left unharvested for long periods of time, *E. saccharina* infestation levels have the potential to get out of control. For example, the relatively long third crop cycle of field 1 gave rise to high infestation levels in the next cycles of fields 2 and 3.

Table 8.1: The lengths of crop cycles of fields 1, 2 and 3 under consideration.

	Length of crop cycle				
	cycle 1	cycle 2	cycle 3	cycle 4	cycle 5
field 1	16	20	16	12	15
field 2	12	15	12	18	18
field 3	12	18	12	15	12

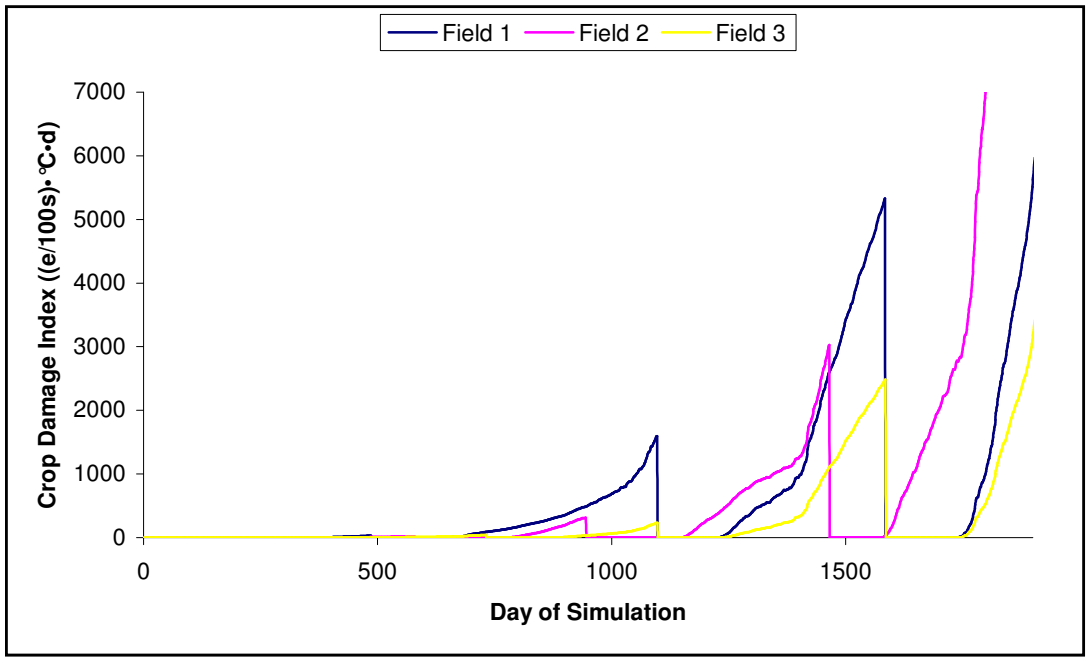

Figure 8.5: Spatial model output showing the damage index for each field for varying crop cycle lengths as given by Table 8.1

8.6 Some remarks

The spatial model presented in this chapter is an exploratory model. It was set up to investigate the effect of neighbouring fields on the infestation levels of a new field. In this regard, it has shown that the *E. saccharina* model developed in Chapter 3 needs some improvement as neighbouring fields will have a big influence on the infestation level rather than the assumption that moths 'from somewhere' will infect the field being modeled.

The simulation spatial model presented in this chapter also has its own shortcomings in that for it to give the insights discussed above, the field cycles have to be chosen carefully in order to ensure that it does not model a fallowed field 2 in which case future populations will be non-existent since the initialization process will have been stopped after the first crop cycle.

Chapter 9

Conclusion

The objective of this study was to develop a simulation model of the sugarcane pest *E. saccharina* that would take into account the condition of the crop host on its population dynamics. This was in order to build a tool to aid researchers at SASRI who have since 1974 been investigating various means of controlling the pest. The SASRI research programs include biological control, chemical control, crop management and varietal resistance. The model developed therefore had to have the capability to simulate biological control strategies, insecticide application strategies and crop carry-over scenarios while taking into account the condition of the host crop. To take the condition of the crop into account, the model was structured to use output

from the sugarcane growth model, CANEGRO, that have shown to influence the rate of attack of the crop by the pest as well as the crop susceptibility index rating (a rating system used by SASRI to rate the crop's susceptibility to attack by *E. saccharina*). The CANEGRO output used in the pest model are crop water stress (*E. saccharina* 'loves' stressed sugarcane) and dead leaf numbers for egg laying sites.

In order to give an indication of the damage caused by the pest on sugarcane throughout the crop's growth cycle, a damage index was defined. The damage index is a measure of the number of stalk borers that have been feeding on the sugarcane stalk during its growth cycle. It also takes into account the influence of temperature on the development of the pest and on the amount of stalk tissue consumed. The damage index as defined makes it possible to estimate the length of stalk bored by *E. saccharina*. Using this, together with total stalk length calculated in the CANEGRO model, the percent stalk length bored can be found. Percent stalk length bored is then used to give an indication of the reduction in sugarcane quality and hence the possible losses in revenue that can be incurred due to attack by *E. saccharina*.

When investigating the crop carry-over decision, the damage index defined in the model proved to be a powerful tool because with the aid of the model, the CANEGRO model and historical weather data, predictions on the percent stalk length bored during the carry-over period could be made and hence the expected gains or reductions in RV could be determined. The decision would then be based on expected economic returns. The decision criterion

currently in use only employs the level of larval count at the decision date. As argued earlier, the larval count recorded could be influenced by many factors, including the timing of the survey. Because surveys also measure the length of stalk bored, it would be recommended that this should also be taken into account in the carry-over decision. Model results indicate that percent stalk length bored at the end of the carry-over period will be between two to three times that recorded at the decision date and so, if the percent stalk length bored is known at the decision date predictions can be made about possible levels when mills re-open. The level of e/100s recorded at the decision date on the other hand, cannot be associated with percent stalk length bored and so cannot be directly linked to potential gains or losses in RV.

When investigating insecticide application strategies, the cohort structure of the model made it possible to target specific larval age groups whose susceptibility to insecticides varies. Results of these investigations give the relationships between the duration of insecticide effect and the reduction in percent stalk length bored and percent gains in RV of the crop. Even though it was not possible to compare the costs and benefits of insecticide release strategies, results do give an indication of the extent to which the various strategies can improve RV.

The results of biological control strategies investigating the use of *S. parasitica* as a possible biological control agent against *E. saccharina* were not very encouraging. This was because the simulated parasitoid releases failed to establish themselves on *E. saccharina*. The populations did not recover during

the cold months of the simulations. The simulation results show the importance of the timing of releases on their effectiveness. Relationships between timing, magnitude of releases and frequency of releases with the reduction in percent stalk length bored and gains in RV were found. It was demonstrated how even though certain release strategies can give rise to marked gains in RV, the overall benefit per release may be better for strategies which show lower gains in RV. This is important because the cost of releases, no matter how effective the releases are in reducing damage, should not exceed the benefit in RV gains.

A sensitivity analysis of the model parameters has been carried out. This was done by increasing or decreasing their values by 10% and noting the resulting change in model output. The parameters where then ranked according to which had the most impact on model output for these changes. The rankings derived from the sensitivity analysis give an indication of which parameters need to be more accurately measured.

Overall, the work presented here has demonstrated the effect of various control strategies aimed at reducing damage to sugarcane due to the pest *E. saccharina*. It has been illustrated how the model can be used to aid the carry-over decision based on a new criterion that is not difficult to implement and which, in our opinion, gives a better indication of what to expect over the carry-over period.

The influence of neighbouring fields on model output were also investigated

by developing an exploratory spatial model. While the spatial model has limitations, it was able to indicate that there is room for improvement in the *E. saccharina* model developed in Chapter 3. It also indicated how certain farming practices may help reduce damage levels to the crop.

It is hoped that the model presented here has laid a good foundation for future improvements aimed at improving the fit with actual field data. These include, but are not limited to, taking into account the availability of natural predators of *E. saccharina* such as ants and the spatial dispersal behaviour of *E. saccharina* moths to adjacent fields. The latter may give insight into the initialization of the current model where instead of using the seasonal moth peak trend to determine infestation onto a young field, simulations for surrounding fields would be responsible for supplying immigrants onto the young field.

Some of the equations used in the model have the possibility of causing it to exhibit "chaos" with sensitivity to the initial conditions. Care should therefore be taken when using the model as a decision support tool and studying these possibilities should be part of future considerations for improvements to the model.

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Appendix A

The multiplier functions

A.1 S-shaped multiplier function with positive slope

We present two equations that can be used for the S-shaped function with positive slope used in the model (see Figure 4.2(a)).

One is given in Uys (1984): For $A > 1,0 < B < 1,0 < g$ the function given

by

$$f(A, B, g, x) = \frac{A}{1 + D \cdot Exp(-Cx^r)} \tag{A.1}$$

where

$$\begin{aligned} D &= (A/B) - 1 \\ C &= \ln[D/(A-1)] \\ r &= gA/[(A-1)C] \end{aligned}$$

has the properties

(1) $f(A, B, g, 1) = 1$,

(2) $\lim_{x\to\infty} f(A, B, g, x) = A$,

(3) $\lim_{x\to 0} f(A, B, g, x) = B$, and

(4) $d[f(A, B, g, x)]/dx|_{x=1} = g$.

The other is given in Saeed (1984): For $K > 1$ and $m > 1$ the function given by

$$g(K, m, x) = \frac{K}{1 + m(K-1) \cdot Exp[-x \ln(m)]} \tag{A.2}$$

has the properties

(1) $g(K, m, 1) = 1$,

(2) $\lim_{x\to\infty} g(K, m, x) = K$ and

(3) the parameter m is responsible for the steepness of the S-shape when K is fixed (see Figure A.1).

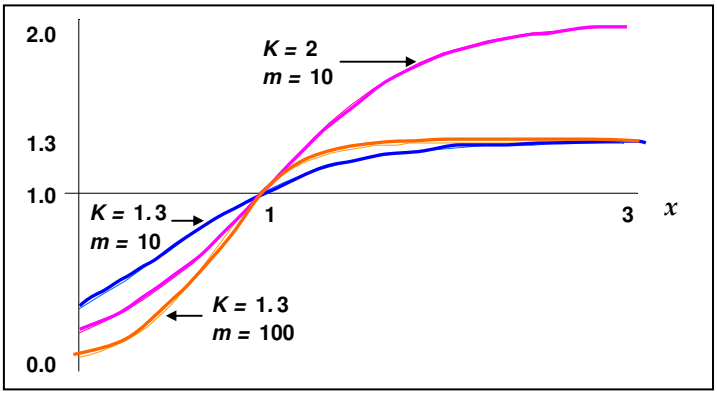

Figure A.1: Plots of the function $g(K, m, x)$ for various values of K and m.

A.2 S-shaped multiplier function with negative slope

An equation for an S-shaped function with negative slope can be found in Saeed (1984) (see Figure 4.2(b)): For $K > 1$ and $m > 1$, the function given by

$$h(K, m, x) = \frac{K/(K-1)}{x^m + 1/(K-1)} \tag{A.3}$$

has the properties

(1) $h(K, m, 1) = 1$,

(2) $\lim_{x\to 0} h(K, m, x) = K$,

(3) $\lim_{x\to\infty} h(K, m, x) = 0$ and

(4) the parameter m is responsible for the steepness of the S-shape when K is fixed (see Figure A.2).

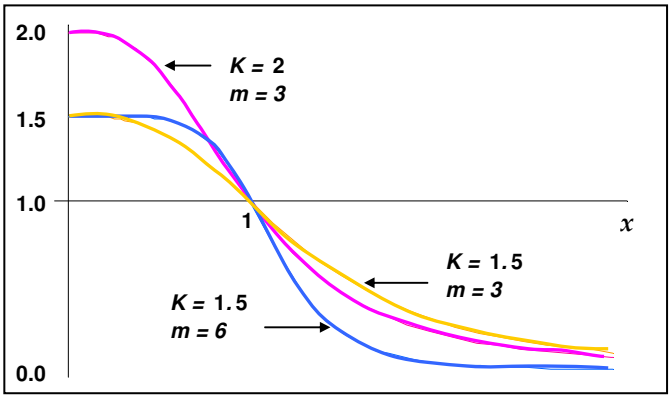

Figure A.2: Plots of the function $h(K, m, x)$ for various values of K and m.

A.3 The crop water stress multiplier function

The crop water stress multiplier function whose shape is shown in Figure 3.3 (note the comment about a simpler function on page 34) is given by the function

$$g_{\text{stress}}(A, B, h, x) = \frac{A}{1 + D \cdot Exp[-C(2(1-x))^r]} \tag{A.4}$$

where

$$\begin{aligned} D &= (A/B) - 1 \\ C &= \ln[D/(A-1)] \\ r &= hA/[(A-1)C] \end{aligned}$$

It is a modification of Equation A.1 and has the following properties for $A > 1$, $h > 0$, $0 < B < 1$:

(1) $g_{\text{stress}}(A, B, h, 0.5) = 1$,

(2) $\lim_{x \to 1} g_{\text{stress}}(A, B, h, x) = B$,

(3) $d[g_{\text{stress}}(A, B, h, x)]/dx|_{x=0.5} = -2h$

A.4 The 'quality of life' index multiplier function

The 'quality of life' index multiplier function g_{ind} shown in Figure 3.4 is a function given by

$$g_{\text{ind}}(K, m, x) = 1 + (K - 1)x^m \tag{A.5}$$

It has the following properties

(1) $g_{\text{ind}}(K, m, 0) = 1$,

(2) $g_{\text{ind}}(K, m, 1) = K$,

(3) $g_{\text{ind}}(K, m, x)$ is a straight line with slope 1 when $m = 1$, concave up when $m > 1$ and concave down when $m < 1$ (see Figure A.3).

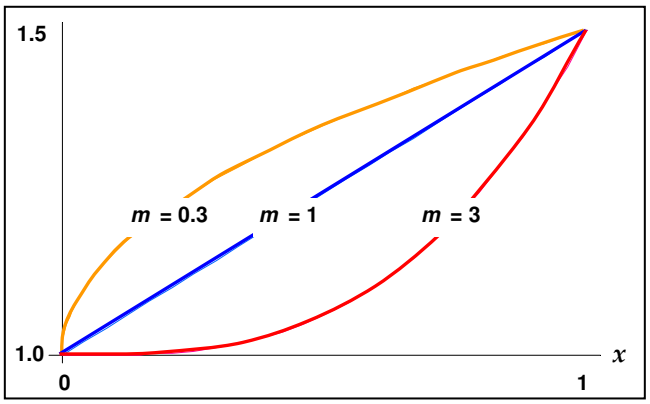

Figure A.3: Plots of the function $g_{\text{ind}}(K, m, x)$ for $K = 1.5$ and various values of m.