

MODELLING POPULATIONS OF THE STALK-BORER *Eldana saccharina*, BASED ON THE CONDITIONS OF SUGAR CANE AS A HOST PLANT

PETROVIOUS HORTON, JOHN HEARNE, JOSEPH APALOO

School of Mathematics, Statistics and Information Systems, University of Natal, P/Bag X01. Scottsville 3209

Abstract

Eldana saccharina Walker (Lepidoptera: Pyralidae) has caused high yield losses in KwaZulu-Natal sugarcane. Early cutting is one of a number of methods being used to reduce losses due to *E. saccharina* infestations. A cohort based age-structured mathematical model was developed to enable sugarcane growers to simulate the effect of various seasonal conditions on *E. saccharina* infestation levels. The model takes into account the contribution of the condition of sugarcane (determined from the CANGRO model) to population dynamics of *E. saccharina* and calculates a crop damage index on each day of the simulation. Temperature dependence of the duration of each stage in the *E. saccharina* life cycle is an added parameter of the model. By running CANGRO and *E. saccharina* models together, insight is gained on cutting cycle length determinations.

Results show that the model generally under-estimates *E. saccharina* infestation levels but the timing of larval peaks coincides with field data. Model results to illustrate the effects of various seasonal conditions on *E. saccharina* infestation levels are also presented.

Introduction

Various measures of control of *Eldana saccharina* Walker (Lepidoptera: Pyralidae) are being investigated by the South African Sugar Association Experiment Station (SASEX). These include insecticide application, parasitoid release (Conlong, 1997; Carnegie, Conlong & Graham, 1985; Carnegie & Leslie, 1979) and the early cutting of cane.

For the successful implementation of any of these strategies, it is desirable to be able to predict the optimal date for their execution. It is also desirable to predict how successful the control measure being implemented will be. Undertaking expensive and long-term field trials could help answer these questions; however computer experimentation, because of its relatively lower cost, has become more widely used in science.

Van Coller (1992), Hearne, *et al.*, (1994) and Uys, *et al.*, (in preparation) developed computer implemented mathematical models to investigate insecticide application and parasitoid release strategies for the control of *E. saccharina*. Van Coller (1992) and Hearne, *et al.*, (1994), found that whilst parasitoids helped to reduce populations of *E. saccharina*, the populations were still not at acceptable levels. Costs associated with rearing large numbers of parasitoids in order to reduce populations of *E. saccharina* to acceptable levels have to be weighed against costs associated with damage. Cultural control, which includes early cutting of cane, is still the preferred method of control by sugarcane farmers.

The decision whether to cut cane or not is normally made in October and November, just before the mills close. It is based on age of cane, *E. saccharina* infestation levels at that time of the year and expected infestation levels when the mills reopen in March. The models developed by Van Coller (1992); Hearne, *et al.*, (1994) and Uys, *et al.*, (in preparation) can give insight into *E. saccharina* populations at the decision date. These models, however, do not take the dynamics of sugarcane into account. They also do not model the temperature dependence of the duration of each stage in the life cycle of *E. saccharina*.

The aim of this paper is to formulate a mathematical model designed to answer the question of early cutting of cane. The model takes into account the condition of sugarcane, based on output from the CANGRO model (Inman-Bamber, 1991), as well as the dependence on temperature of the duration of each stage in the *E. saccharina* lifecycle.

Model Description

The *E. saccharina* model (hereafter referred to as “the model”) is designed to interact with the CANGRO model (Inman-Bamber, 1991). Inputs into the model are air temperature, together with dead leaf numbers per stalk and crop water stress index, taken as outputs from the CANGRO model (see Figure 1). Air temperature is used to model the physiological age of *E. saccharina*. 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 for ovipositing on dry cane leaf material (Leslie, 1990; Carnegie & Smaill, 1982). Crop water stress index is used to estimate the nutritional value of the cane stalk with respect to *E. saccharina* development. The number

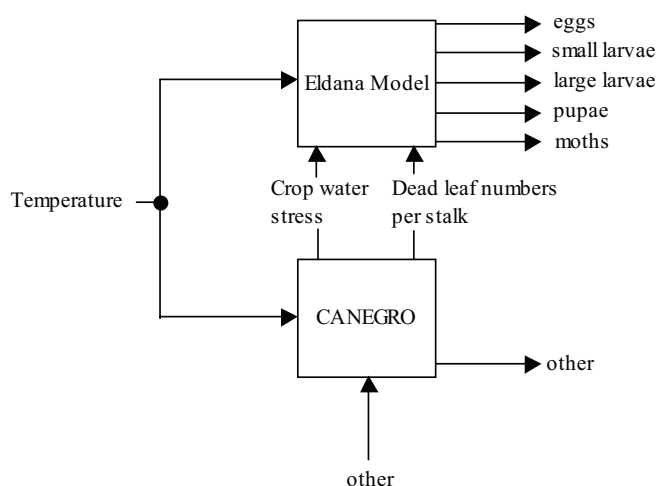


Figure 1. Interaction between the model and CANGRO.

of *E. saccharina* larvae that bore into the cane stalk is influenced (amongst various other factors) by how stressed the crop is at the time and thus the crop water stress index is also used in the calculation of infestation levels.

For the purposes of the model, the life cycle of *E. saccharina* is divided into five distinct stages, namely, the egg, small larva (includes instars I-III), large larva (includes instars IV and above), pupa and moth (or adult) stages. The reason for having two larval stages is that crop damage is due to the larger larvae and knowing the exact numbers of these at any time will aid in estimating damage caused.

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

further subdivided into a number of cohorts. Since the model is run on a daily time-step (i.e. the model updates population numbers on a daily basis), a cohort is defined as 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 can be no two different cohorts that began on the same day. For example, all eggs laid on a particular day are grouped into one egg cohort.

As soon as large larvae mature to pupae, the cohort structure changes. A pupae cohort can only come from one particular cohort of large larvae, but each cohort of large larvae can result in a number of pupae cohorts, the distinguishing factor being the day on which those members of the cohort of large larvae

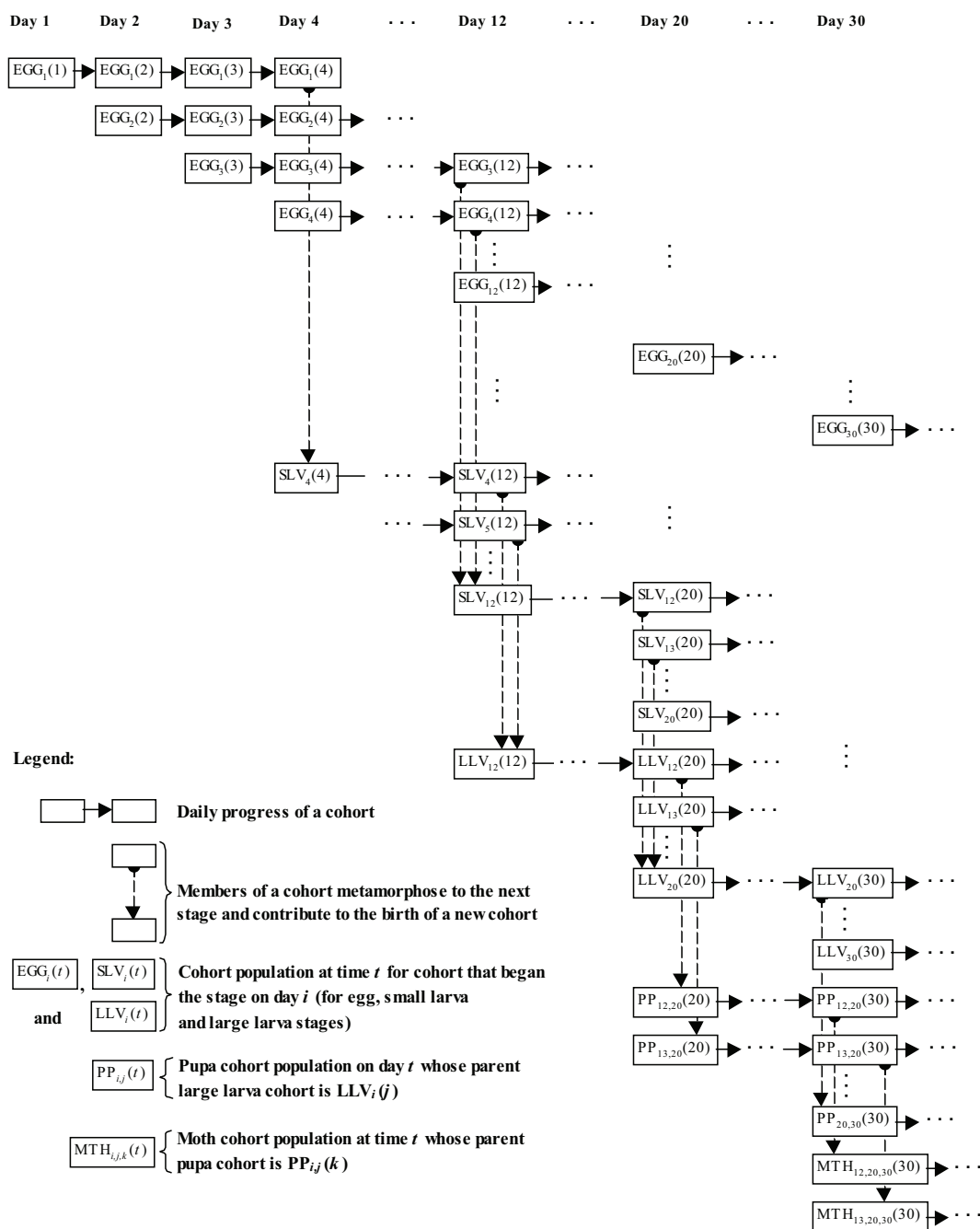


Figure 2. The interactions between the various cohorts in the model showing how new cohorts come from older ones.

mature into pupae. Thus a pupae cohort has two distinguishing features: the day on which it started and the cohort of large larvae it came from. The reason for doing this is to be able to monitor crop and temperature conditions experienced by the “parent” cohort of large larvae. These conditions are carried through to the moth stage to be used to determine egg-laying rates for the next cycle. Moth cohorts are set up in a similar manner by taking into account the day they begin and the pupa cohort they result from. Details of how new cohorts are created from old are shown in Figure 2.

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 egg population on any given day will contain egg cohorts aged from one day onwards. Those that hatch will come from the egg cohorts that have reached a certain physiological age and the actual numbers of eggs that hatch from each cohort are determined by a function of the physiological age of the cohort.

Since the time spent in each stage in the *E. saccharina* lifecycle is temperature dependent, the number of degree-days ($^{\circ}\text{C}\cdot\text{d}$) accumulated above a threshold temperature for growth measures the age of a cohort instead of the actual number of days it has lived. Way (1995) calculated the duration (“thermal constants”), in $^{\circ}\text{C}\cdot\text{d}$, of each stage in the *E. saccharina* lifecycle as well as the threshold temperature required for development for each stage (see Table I). Using the threshold temperature for development and the average temperature for the day, the model updates the number of $^{\circ}\text{C}\cdot\text{d}$ accumulated by a cohort from one day to the next by an equivalent of $(T_{\text{ave}}(t) - T_t) ^{\circ}\text{C}\cdot\text{d}^1$, where $T_{\text{ave}}(t)$ is the average temperature ($^{\circ}\text{C}$) on day t and T_t is the threshold temperature ($^{\circ}\text{C}$) for development for the stage that the cohort is in.

When the model is run concurrently with 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 daily by moths that are “lingering about” until the system produces its own moths. As soon as this happens, the moths produced by the model take over the creation of new egg cohorts until the crop is harvested. The number of eggs assumed to be laid initially depends on the crop variety being grown, as the varieties tend to offer different resistance levels to *E. saccharina* infestations (Keeping, pers. comm.; Carnegie, 1981). The SASEX Agronomy department provided crop variety sensitivity to *E. saccharina* for each of the crop varieties used in the model as an index based on larval activity (the index given corresponds with the

Table I. Stage-specific temperature thresholds for development and thermal constants for *E. saccharina*. (Source: Way, 1995.)

Stage	Temperature Threshold for development ($^{\circ}\text{C}$)	Thermal Constant ($^{\circ}\text{C}\cdot\text{d}$)
Egg	5.3	119
Small Larva	10.2	219
Large Larva	10.2	405
Pupa	10.7	160

E. saccharina susceptibility ratings supplied by Keeping, pers. comm. shown in Table II). For these crop varieties, the sensitivity index varied from 5 to 9, where an index rating of 5 was taken as standard and for each index rating above 5, *E. saccharina* activity was increased by 15%. Thus, initial egg cohorts contained 2 eggs per 100 stalks of cane for fields rated 5 and the figure was increased accordingly for other fields. The index rating was also applied in adjusting the mortality rates of *E. saccharina* larvae. The model assumes that no other stages in the *E. saccharina* lifecycle are present when the initial egg population is introduced.

Once cohorts have been established, changes in their population numbers are due only to deaths and members maturing to the next stage (see Figure 3). No new members are recruited into a cohort once it has been established.

At each time step, the model updates each cohort’s physiological age, calculates losses based on natural daily mortality rates, creates new egg cohorts from the total number of eggs laid by all moths on that day and creates other stage cohorts from those maturing from one stage to another. The model also updates and keeps track of a *crop water stress index* and a *temperature index* for the large larva cohorts based on crop water stress and average temperature, respectively, on that day. These indices are carried through to the resulting moth cohorts to be used in a function that determines the fecundity rate of the corresponding cohort.

To correspond with common practice in the sugar industry, the model calculates *E. saccharina* infestation in terms of the number of *E. saccharina* per 100 stalks of sugarcane crop. The notation of e/100s used by Hearne et al., (1994) is adopted here

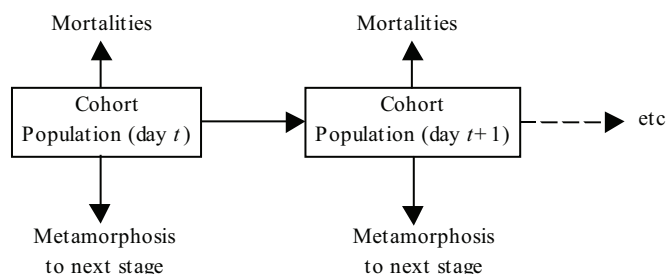


Figure 3. The daily progress of a cohort showing the factors affecting its population numbers.

Table II: Ratings of crop variety to *E. saccharina* susceptibility. Source: Keeping, pers. comm.

Crop variety	NCo376	N13	N11
<i>E. saccharina</i> susceptibility rating	5	7	9

Table III. Number of eggs laid per moth on each day after emerging based on model calibration

Moth Age (days)	1	2	3	4	5
Number of eggs laid	3	7	15	8	6

Table IV. Threshold temperatures used in the model after calibration.

Stage	Egg	Small Larva	Large Larva	Pupa
Threshold Temperature ($^{\circ}\text{C}$)	5.3	10.2	11.7	10.7

to denote this. In the model, numbers of large larvae on any given day may not give an accurate representation of crop damage since the numbers vary from day to day. At present, it is still not clear how the numbers of large larvae in cane stalks contribute to damage. What is clear is that *E. saccharina* is responsible for the losses in sucrose content of cane. We can however, estimate the amount of cane tissue lost due to *E. saccharina*. We note that each large larva present in cane stalk for, say n days, will cause damage equivalent to damage caused by n larvae in one day alone. Thus, a damage index must use cumulative totals of large larvae from the first day of the simulation to the present day. The problem with using cumulative totals of larvae as above is that we would get a damage index that is always increasing, not allowing for compensation by the crop growing (if previous damage was not too severe to cause total crop failure). We thus propose a damage index defined as follows: the *damage index* on any given day in the simulation of the growth cycle of the crop is the cumulative total of large larva numbers (e/100s) up to the day divided by the total number of days in the simulation. This gives an average of the number of *E. saccharina* larvae present in the cane per day. A link between this damage index and actual field damage has to be investigated.

The model described above was implemented in a computer program using the Fortran90 programming language. The mathematical details of the model are to appear in a later paper.

Results and Discussion

Model calibration

Field data of *E. saccharina* numbers were supplied by SASEX for four fields of sugarcane crop of varying resistance to the pest. The model was run with CANEGRO for the same period over which the field data were collected and the results were compared with the field observations. Model parameters such as fecundity rates of moths and threshold temperatures were varied until a fit close to actual data was achieved. The final parameters used in the model are given in Tables III and IV.

Initial model calibration was done using field data for Mtunzini field 013 (variety NCo376; *E. saccharina* sensitivity index 5). Since the model does not distinguish between trashed or burnt fields, data sets for burnt blocks were used because the model assumes an *E. saccharina* free field in its initialisation and burning eliminates chances of *E. saccharina* eggs remaining in the field after harvest. It has to be noted that the field data vary widely from block to block (see Figure 4), thus model calibration was done using the average of the data sets from the two blocks (see Figure 5).

After the initial calibration was done, validation using the remaining data sets for fields at La Mercy (field 209, variety NCo376, sensitivity index 5 and field 701, variety N13, sensitivity index 7) and Mtunzini (field 042, variety N11, sensitivity index 9), was attempted. Because validation failed, it was then decided to vary model parameters such that a balance was reached for all four fields, i.e. all four data sets were then used in the calibration of the model. The final parameters used in the model are given in Tables III and IV. Figures 4 to 11 show model results compared with actual field data. The even numbered figures show the variation in field data for various blocks within the same field, illustrating the difficulties faced in the calibration stages, whilst the odd numbered figures show the averages of these field data that were used in the calibration.

Figures 4 to 11 show that (with the exception of Figure 11) the model in general under-estimates *E. saccharina* infestation lev-

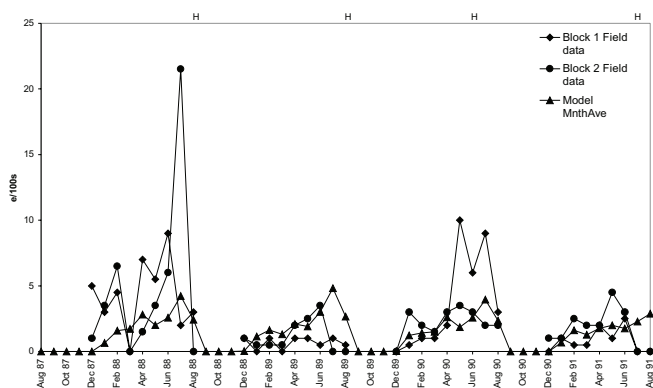


Figure 4. Model results for field 013 (Mtunzini) plotted with field data sets for two burnt field blocks. "H" denotes harvest date.

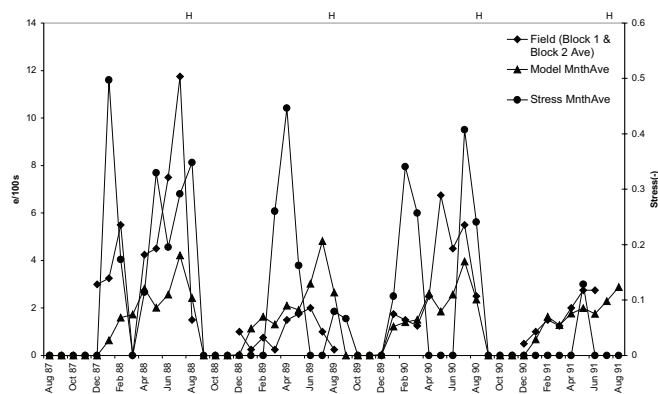


Figure 5: Model results for field 013 (Mtunzini) with the average of the two data sets shown in Figure 4. The monthly average stress is also plotted to illustrate its effect on *E. saccharina* infestation levels.

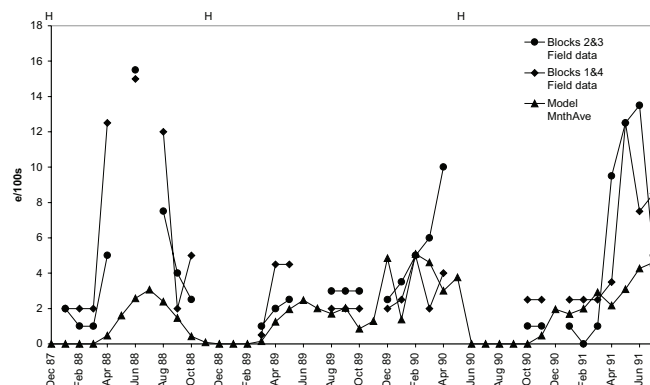


Figure 6. Model results for field 209 (La Mercy) with two field data sets for burnt blocks. "H" denotes a harvest date.

els with closest fits coming from fields growing crop variety NCo376 (Figures 5 and 7) followed by that growing crop variety N11. It should also be noted that the model in general is able to predict the timing of larvae peaks.

Discrepancies between the model results and actual field data could be due to the following factors, which still have to be investigated further. (1) Field data readings were taken on a particular day in the cane growth cycle whereas the model results plotted are averages of daily numbers of large larvae over the month. (2) Development times for each stage in the lifecycle

depend on threshold temperatures and if those used in the model are not accurate, discrepancies could arise. Also, the large larva stage, which spends its life inside the cane stalk, may experience a different temperature to the air temperature used in the model and their development times would be affected (Way, pers. comm.).

Testing model response to temperature and water stress

The model was tested for its response to various seasonal conditions by running it with CANEGRO for cane fields at Tongaat during wet (Jan-Dec, 1987), dry (Jan-Dec, 1994), hot (Jan-Dec, 1993) and cold (Jan-Dec, 1982) seasons. The crop variety grown during this season was assumed to be NCo376

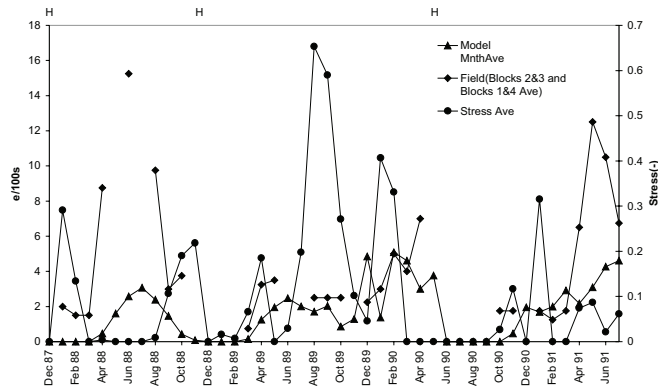


Figure 7. Model results for field 209 (La Mercy) with the average of the two data sets shown in Figure 6. Average monthly stress is also shown.

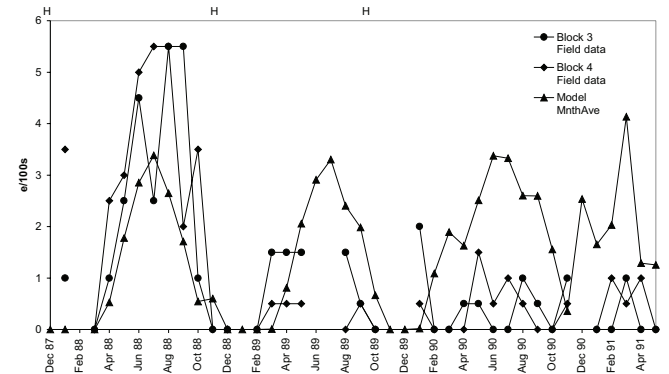


Figure 10. Model results for field 701 (La Mercy) with plots of two data sets for burnt field blocks at La Mercy field 701.

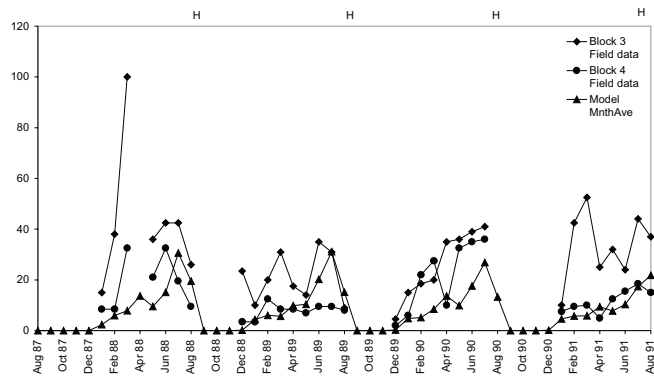


Figure 8. Model results for field 042 (Mtunzini) with two sets of field data for burnt field blocks.

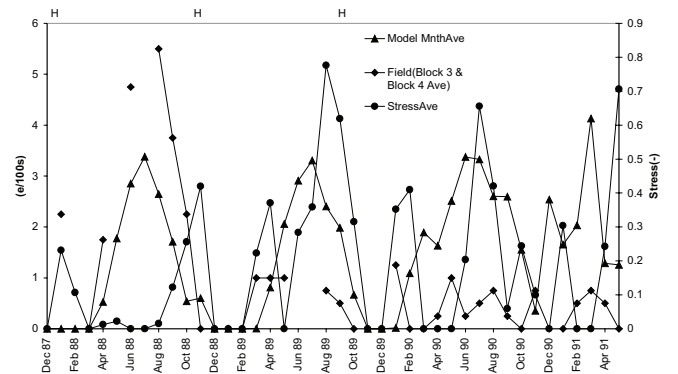


Figure 11. Model results for field 701 (La Mercy) with the average of the two data sets shown in Figure 10 and the monthly average of cane stress.

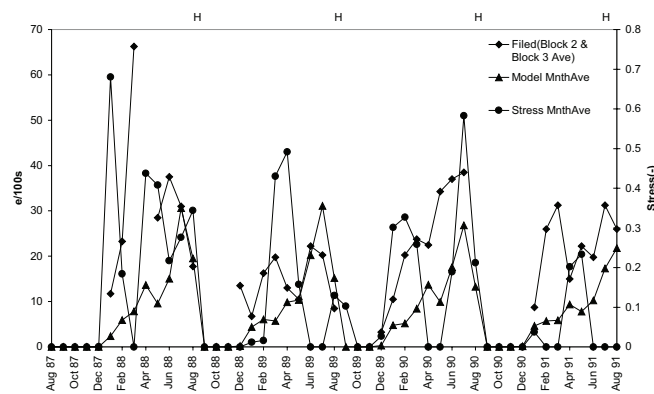


Figure 9. Model results for field 042 (Mtunzini) with the average of the two field data sets shown in Figure 8 and the monthly average of cane stress.

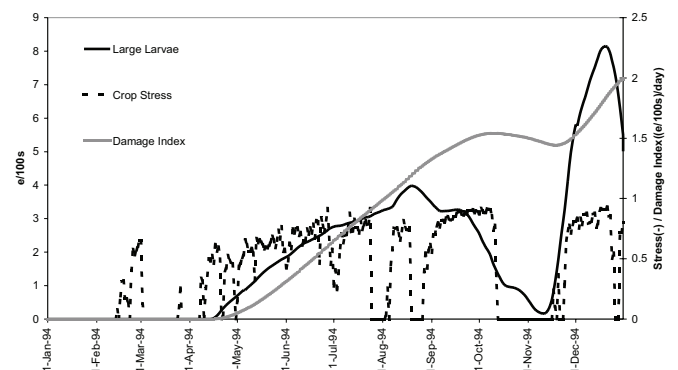


Figure 12. Model results for a dry season at Tongaat showing the damage index, crop water stress and e/100s.

with sensitivity rating 5. The results of these simulations are shown in Figures 12 – 15. To get a feel of how the various seasonal changes contribute to crop damage, we have also plotted the damage index discussed in the section on model description.

Comparing Figures 12 and 13, we see that the model performs as expected under dry and wet seasons in the sense that numbers of large larvae are higher during the dry season (eldana loves stressed cane). Note also that the damage index goes up to as much as 2 e/100s/day during the dry season compared to about 1.5 e/100s/day during the wet season.

When we compare the results from running simulations for hot (Figure 14) and cold (Figure 15) conditions, we see a higher incidence of *E. saccharina* larvae during the cold season than during the hot season. To explain this we note first that the time spent in each stage of the *E. saccharina* lifecycle will be longer during the cold season, and since each stage duration is different from another, some stages will end up with larger population numbers. Another factor that should not be overlooked is crop stress. We note that during the later part of the cold season, crop stress is higher than that during the corresponding period for the hot season, thus the higher borer incidence for the cold season.

Using the model to determine a harvesting strategy

To illustrate how the model can be used to aid the decision whether to harvest or not, the model was run for a hypothetical field at Mtunzini of variety N11 (sensitivity index 9) grown

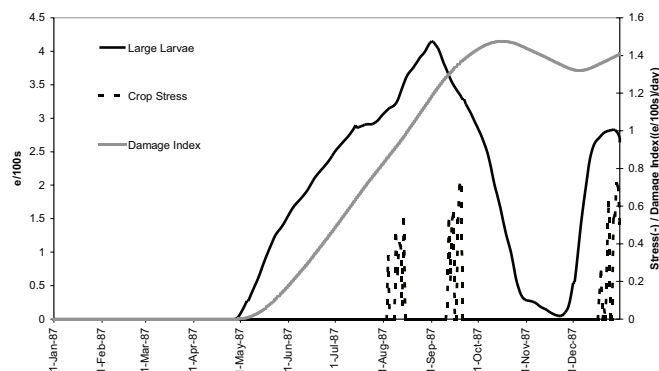


Figure 13. Model results for a wet season at Tongaat showing the damage index, crop water stress and e/100s.

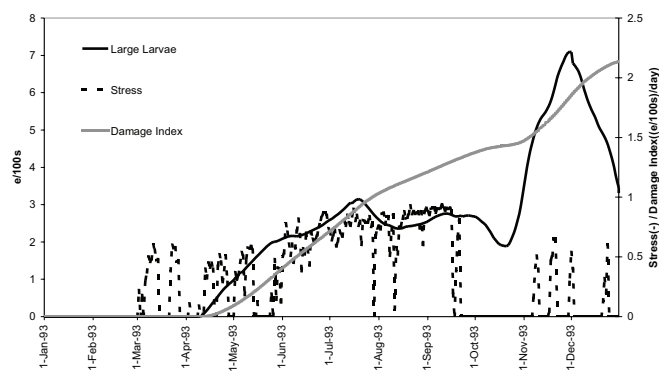


Figure 14. Model results for a hot season at Tongaat showing the damage index, crop water stress and e/100s.

between November 1979 and December 1981. Since the decision whether to harvest or not is normally made during October/November months, the model was run with typical temperature and crop stress from November 1979 to November 1980. From December 1980, the temperature and crop stress were increased or decreased by 15% to investigate model results for hot, cold, dry and wet weather scenarios. These results are shown in Figure 16. As expected, the simulated dry and hot scenarios show a higher damage index than the wet and cold scenarios. It is also interesting to note that the “wet” curve coincides with the curve showing actual temperature and crop water stress conditions during the simulation period. This could indicate that the simulation period chosen was actually a wet season.

Based on weather predictions, the grower can thus simulate damage during the carry over months and depending on how tolerable the expected damage levels are, a decision can be made whether to harvest in November or wait until the mills reopen in March/April. For example, if it is agreed that a damage index of 10 e/100s/day is too severe, the grower of the field with results shown in Figure 16 would be advised to harvest before the mills close if a dry carry over season is predicted because by mid March the damage index will have gone beyond 10 e/100s/day.

Conclusion

A model of the sugarcane pest *E. saccharina*, to be run concurrently with the sugarcane growth model CANEGRO, has been formulated. Temperature effects on the physiology of

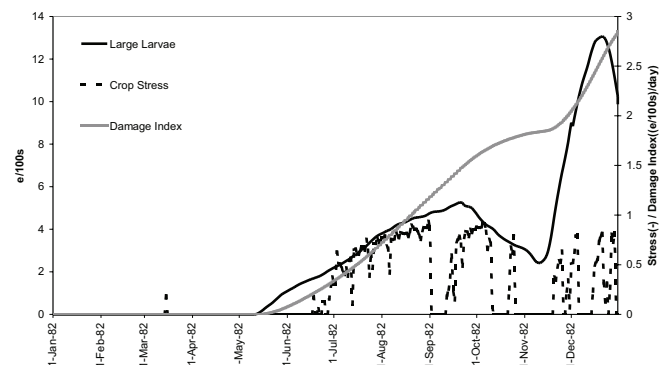


Figure 15. Model results for a cold season at Tongaat showing the damage index, crop water stress and e/100s.

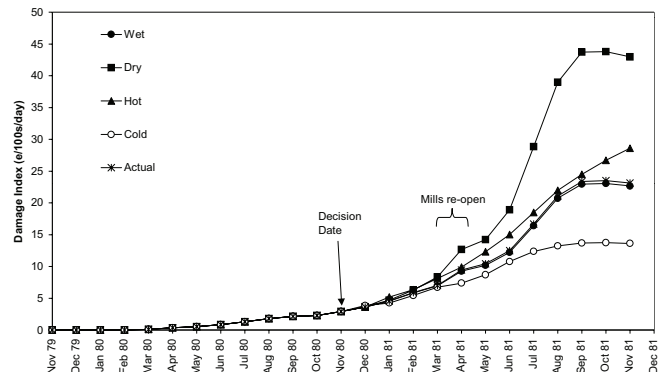


Figure 16. Model results for harvest scenarios for Mtunzini field crop.

E. saccharina and crop water stress contribution to infestation levels were considered in the development of the model. Some difficulty in model calibration was experienced due to the fact that field data showed differences in larvae incidence for different blocks within the same field and crop variety grown. Model results show that the model in general under-estimates *E. saccharina* infestation levels but the timing of larvae peaks coincides with field data. The model performs as expected under various seasonal scenarios.

The model as described can be used to estimate a crop damage index at any time during the crop cycle. The damage index calculated has still to be linked to actual crop damage in the field. In order for cane growers to be able to use the model as a decision making aid on whether to harvest or not, an agreement has to be reached on a critical damage index at which losses to profit from the crop are irrecoverable. By running CANEGRO together with the model, the day on which this critical damage index is reached can be pinpointed and the grower can be advised to harvest his crop. This aspect has to be investigated further.

Acknowledgements

Dr DE Conlong (Entomology Dept, SASEX) and Dr A Singels (Agronomy Dept, SASEX) provided helpful comments on the manuscript; Mr. C Bezuidenhout (Agronomy Dept, SASEX) provided assistance with CANEGRO data and Mr. MJ Way (Entomology Dept, SASEX) provided assistance with *E. saccharina* parameters. This work was funded in part by the South African Sugar Association.

REFERENCES

- Carnegie, A.J.M. (1981). Combating *Eldana saccharina* Walker: A progress report. Proc. S. Afr. Sugar Technol. Assoc. June 1981.
- Carnegie, A.J.M, Conlong, D.E. and Graham, D.Y. (1985). Recent introductions of parasitoids against *Eldana saccharina* Walker (Lepidoptera: Pyralidae). Proc. S. Afr. Sugar Technol. Assoc. 59: 160-163.
- Carnegie, A.J.M and Leslie, G.W. (1979). Attempts at the biological control of *Eldana saccharina* Walker (Lepidoptera: Pyralidae). Proc. S. Afr. Sugar Technol. Assoc. 53: 116-119.
- Carnegie, A.J.M. and Smail, R.J. (1982). Pre-trashing of sugarcane as a means of combating the borer *Eldana saccharina* Walker. Proc. S. Afr. Sugar Technol. Assoc. 56: 78-81.
- Conlong, D.E. (1997). Biological control of *Eldana saccharina* Walker in South African sugarcane: constraints identified from 15 years of research. Insect Sci. Applic 17(1): 69-78.
- Hearne, J.W., van Coller, L.M and Conlong, D.E. (1994). Determining strategies for the biological control of a sugarcane stalk borer. Ecol. Modelling 73: 117-133.
- Inman-Bamber, N. G. (1991). A growth model for sugar-cane based on a simple carbon balance and CERES-Maize water balance. S. Afr. J. Plant & Soil 8: 93-99.
- Leslie, G. W. (1990). The influence of dead leaf material on the oviposition behaviour of *E. saccharina* (Lepidoptera: Pyralidae) in sugarcane. Proc. S. Afr. Sugar Technol. Assoc. 64: 100-102.
- Pruess, K.P. (1983). Day-degree methods for pest management. Environ. Entomol. 12: 613-619.
- Uys, P, Apaloo, J, Hearne, J.W., Conlong, D., Way, M. (in preparation). Cohort based dynamics of a stalk borer.
- van Coller, L.M. (1992). Optimal biological control strategies for a problem in the sugar industry – a mathematical modelling approach. Unpublished M.Sc. Thesis, Department of Mathematics and Applied Mathematics, University of Natal, Pietermaritzburg, South Africa.
- Way, M.J. (1995). Developmental biology of the immature stages of *Eldana saccharina* Walker (Lepidoptera: Pyralidae). Proc. S. Afr. Sugar Technol. Assoc. 69: 83-86.

¹ Various ways of estimating degree-days accumulated are discussed in Pruess (1983). This particular one was selected over the more common sine-wave method because of its simplicity and also because Pruess argues that the two methods are similar if the minimum temperature does not fall below the threshold temperature. This is the case most of the time in the sugar region of southern Africa.