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A production break strategy for tomato leafminer in Queensland, 1998

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CRC for Tropical Pest Management

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VG502

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Industry Summary

At a Tomato Pest Management Workshop involving growers, researchers, crop consultants, and industry representatives in 1994, the tomato leafminer, *Phthorimaea operculella*, was identified as one of the three most important insect pests for the industry in Queensland (Kay and Walton, 1994). One of the main reasons for its increase in pest status was the shift toward year round tomato production in the more tropical regions, providing the pest with a continuous food source. At the workshop it was suggested that a series of statewide production breaks be introduced to interrupt the food supply of tomato leafminer (TLM). However, very little is known about how long a successful production break needs to be in each of the main tomato growing areas (Lockyer Valley, Bundaberg, and Bowen). This research was designed to help fill that gap in knowledge.

Some of the main factors that could affect how long a production break needs to be are:

- the climate of the region
- the level of post-harvest crop hygiene used by the grower
- whether there are other plants in the area that can also act as hosts for TLM (e.g. weeds).

This project looked at each of these factors and used the information collected to develop a simulation model of a TLM population. The aim of the model was to show how long a production break needs to be in each area and how the factors listed above could affect the success of the break in reducing TLM numbers.

Some of the key findings of this research were:

- The level of crop hygiene used by the grower after the last harvest affected the number of moths that continued to emerge from block (Baynes, 1996). The levels of crop hygiene that were tested included: bare ground (removal of all plant material and plastic mulch), plastic only (removal of all plant material), plastic and stumps (removal of aerial parts of plant), and intact plant (all plant material and plastic mulch remains).
- Weeds that are closely related to tomato plants (i.e. members of the family Solanaceae) were found within and around tomato blocks and some were found to be infested with TLM suggesting that they could act as host plants in the production break period.
- Some weed species may be more suitable hosts for TLM than others. Laboratory studies showed some evidence of preferential laying of eggs on certain species over others, and differences in development of TLM larvae on different weed species (Ford, 1998).
- The simulation model showed that under high to very high levels of post-harvest crop hygiene, the *minimum* required length of a production break in Bundaberg is 27 days in summer and 31 days in winter, and is 25 days in Bowen in summer. Using average to low levels of crop hygiene the length of the production break is increased to 38 days in summer and 44 days in winter in Bundaberg, and 35 days in Bowen in summer. In temperate areas such as the Lockyer Valley, low temperatures and frosts in winter forces a break in tomato production over this time.

Further research is required to more closely examine the role of weeds as alternative host plants for TLM so that we have a better idea of whether these weeds represent a risk to the success of a production break strategy. Data on the biology of TLM could be added to the simulation model as it is collected so that the information the model provides is more 'realistic'. Until that stage, the suggested length for a production break in each of the regions should be considered as conservative, and all solanaceous weeds should be cleared from within and around a block before, during, and after the cropping period. On-farm trials can be carried out to test the initial predictions of the model for a production break under different levels of post-harvest crop hygiene.

Baynes, R. (1996) Post-harvest emergence of the potato tuber moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) from tomatoes, and an evaluation of pheromone trapping. CRC for Tropical Pest Management Vacation Scholarship Research Report, CRC for Tropical Pest Management, Brisbane, Australia. 29pp.

Ford, L. (1998) Suitability of solanaceous weeds as host plants for tomato leafminer, *Phthorimaea operculella* (Zeller). CRC for Tropical Pest Management Vacation Scholarship Research Report, CRC for Tropical Pest Management, Brisbane, Australia. 19pp.

Kay, I.R. and Walton, M.P. (1994) Workshop Report: Tomato Pest Management. Cooperative Research Centre for Tropical Pest Management, Brisbane, Australia. 65pp.

Technical Summary

The tomato leafminer, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) is one of the three most important insect pests of the tomato industry in Queensland. Its increase in pest status is due to a shift toward year round tomato production in the warmer regions therefore providing a continuous food source, together with the development of resistance to previously effective insecticides. A statewide production break strategy would be an effective method to interrupt the food supply of tomato leafminer (TLM) and reduce its pest status, however, very little is known about the optimal length of a production break in each of the main tomato growing regions (Lockyer Valley, Bundaberg, and Bowen).

This research focussed on some of the factors that could influence the required length of a successful production break. These included the climatic conditions in each region, the effect of post-harvest crop hygiene on emergence of TLM adults, the effect of the presence of weeds related to tomatoes (Family Solanaceae) within and around the crop, and the ability of these weeds to support a TLM population. Data on the biology of TLM, particularly the temperature/development relationship for larvae, was also collected. This information was then used to develop a simulation model of a TLM population. The model was designed to estimate the required length of a production break in each of the growing regions, and to demonstrate the effect of post-harvest crop hygiene, and the presence of solanaceous weeds on the potential success of the production break strategy.

The emergence of moths from the block following harvest was examined under a range of levels of post-harvest crop hygiene. Moth emergence was lowest at the highest level of crop hygiene (i.e. bare ground – all plant material and plastic mulch removed), and greatest when the plant was left intact after harvest. The level of post-harvest hygiene adopted by a grower will therefore alter the minimum required length for a production break, with the break being shorter when hygiene levels are high and longer at low hygiene levels.

A survey of solanaceous weeds in the Lockyer Valley and Bundaberg regions showed TLM infestation on some species. Laboratory investigations also revealed that some weed species, particularly the thornapples (*Datura* spp.), were more suitable hosts than others. Preliminary guidelines of the 'risk' of each weed species acting as a significant alternative host plant for TLM have been provided, however, further experimentation on the oviposition preference, establishment, and development of TLM on each species is required. Until the importance of weeds as alternative host plants for TLM is better established, weed management before, during, and after the cropping period will help to reduce the size of the residual population.

The temperature/development relationship for TLM was established under semi-field conditions, and the information used to calibrate the simulation model. Work on the relationship between temperature and development for TLM eggs and pupae would be useful to further calibrate the model and improve the 'realism' of its output.

The simulation model was used to estimate the minimum required length of a production break in each of the growing areas, and to demonstrate the effect of post-harvest crop hygiene and the presence of solanaceous weeds on the success of the break. The model enables a more informed approach to developing production break strategies for each growing region. Once the role of solanaceous weeds as alternative host plants is better understood, the model could be modified to include a TLM lifecycle on weeds. Collection of empirical data on the biology and ecology of TLM, such as the mortality effects of rainfall or local movement of TLM moths, would also be a useful addition to the model and to our overall knowledge of TLM population dynamics.

1.0 Introduction

The tomato leafminer, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) is a worldwide pest of solanaceous crops and also breeds on a variety of solanaceous weeds (Rothschild, 1986). The moth is known by a range of common names that reflect some of its major host plants: potato tuber moth, potato tuberworm, potato moth, and tobacco leafminer.

Tomato leafminer (TLM) is native to the New World but is now distributed throughout many tropical, subtropical, and warm temperate regions of the world. In Australia, cultivated host plants include potato, tomato, eggplant, and chilli (Rothschild, 1986). Although a major pest of potatoes with yield losses up to 25%, TLM has until recently only been considered a minor pest of tomatoes (Rothschild, 1986; Kay and Walton, 1994). In Queensland in particular, damage caused by TLM increased in severity in the late 1980's to early 1990's probably as a result of increased pesticide use to control other pests such as *Helicoverpa* spp., the move toward year round tomato production in some areas, and the development of resistance to previously effective insecticides (Kay and Walton, 1994).

The distribution, biology, ecology, and management of the pest have been well documented, particularly in potatoes (Rothschild, 1986; Trivedi and Rajagopal, 1992). In tomatoes, the larval stage causes economic damage, with larvae destroying the connective tissue of seedlings, mining the leaves of older plants, and tunnelling into fruit (Fullelove, 1992). Infestation of fruit creates openings for secondary rot organisms which can cause fruit fall or rotting during storage (Fullelove, 1992). Because larvae feed in protected sites, such as leaf mines or fruit, the efficacy of many insecticides applied to control this pest is limited (Fullelove, 1992; Kay, 1993).

At a Tomato Pest Management Workshop held in 1994, TLM was identified as being one of the three most important insect pests for the industry in Queensland (Kay and Walton, 1994). Its increase in pest status in Queensland is likely to be due to the shift toward year round tomato production in the more tropical regions, thus providing a continuous food source for the pest. The value of a break in production which "minimis(es) opportunities for founder colonies to develop from the residual resident population or from immigrants" (Rothschild, 1986), along with "the destruction of crop residues, volunteers, weed hosts, and other crop sanitation measures" (Rothschild, 1986), is already recognised. At the workshop it was suggested that a series of statewide production breaks be implemented to interrupt the food supply of TLM thereby reducing its pest status (Kay and Walton, 1994). However, the required length of a production break in each of the tomato growing regions in Queensland was unknown, and research to acquire this information was identified as a priority.

Factors that could influence the length of a production break include the relationship between temperature and development in TLM, the degree of post-harvest crop hygiene adopted by the grower, the presence of alternative host plants, particularly solanaceous weeds, and their ability to support a TLM population. The aim of this project was to investigate these factors, of which to date very little is known, and use this information along with published data in a simulation model that would be useful for predicting realistic production break strategies for each of the growing regions.

The main focus of the project has been to determine the temperature/development relationship for TLM larvae, to conduct a field survey of solanaceous weeds to determine their ability to act as alternative hosts for TLM, and to develop a simple simulation model of a TLM

population. During the project two vacation scholarship students, jointly funded by the CRC for Tropical Pest Management and QFVG, have conducted research that had fundamental links and benefits to the main project. Renee Baynes (1995-6) investigated post-harvest emergence of adult TLM following a range of post-harvest treatments, and carried out an evaluation of pheromone trapping to monitor field populations. Leonard Ford (1997-8) examined the suitability of a range of solanaceous weeds to act as host plants for TLM. Reference to the work of these two students occurs throughout this report, and because of their relevance, both reports are included as appendices.

In a production break strategy the presence of alternate host plants to the crop host can result in failure of the strategy as insect pests can transfer to these plants during the crop-free period. Identification of which plant species can act as hosts to an insect pest is therefore important so that measures can be taken to control or remove these plants from the vicinity of the crop (Broodryk, 1971; Das and Raman, 1994). Up to 60 species of plants have been recorded as hosts for TLM throughout the world and as many as 20 hosts have been recorded in Australia (Rothschild, 1986; Das and Raman, 1994). Variation in preferences for different plant species has been found both within Australia and overseas (Traynier, 1975; Rothschild, 1986), and preferences of local strains of TLM for different host plants, particularly weed species, is largely unknown (Cameron *et al.*, 1997). In terms of control, a species that is highly preferred by TLM will be far more important than a species on which they are rarely found. A survey was therefore undertaken to determine which solanaceous weed species occurred in the Lockyer Valley and Bundaberg tomato growing areas and of these, on which species TLM could be found. If weeds were found to have a role in supporting a TLM population, this information could be included in the simulation model to demonstrate the importance of weed control on TLM numbers.

The relationship between temperature and development for many insects is often examined under laboratory conditions where temperature and humidity are kept constant, and studies of TLM are no exception (Broodryk, 1971; Foot, 1979; Briese, 1980; Horne and Horne, 1991). This type of research provides reference values for a range insect parameters that can be useful in designing further experiments or in constructing simulation models of the insect lifecycle. Indeed, these values have been used to construct the simulation model developed as part of this project. However, to ensure that the model that has been developed is realistically simulating TLM development under field conditions, that is, to 'validate' the model, data on the temperature/development relationship for TLM larvae was collected under more natural environmental conditions. Using a data logger to record the air temperature, and daily monitoring of the development of individual larvae, the aim of this experiment was to collect empirical data that could be used to run the simulation model and compare the model output with the actual development data. In this way, the model can be adjusted so that it more accurately reflects TLM development under field conditions.

To make more informed decisions about the required length of a production break in each of the tomato growing regions, a simulation model of a TLM population was constructed that can be used by researchers, extension specialists, and growers to assess the impact of a production break on the TLM population. Once the simple model had been developed, information collected in other experiments, such as the effectiveness of post-harvest crop hygiene in reducing TLM numbers or the role of weeds as alternate hosts, was added to the basic model. The impact of these different management strategies on the effectiveness of the production break in reducing TLM numbers in the various cropping regions could then be assessed. The model was created using DYMEX software developed by the CRC for Tropical Pest Management.

2.0 Materials and Methods

2.1 Alternative host plant survey

A survey was carried out to determine if solanaceous weeds found in the Lockyer Valley (SE Queensland) and the Bundaberg district (Central Queensland) were infested with TLM, thereby indicating that they may be able to act as alternative host plants in the absence of solanaceous crops.

A total of 39 sites were surveyed in the Lockyer Valley area from 28/11/96 to 23/1/98 (survey interval approx. 40 days) covering an area of approximately 250 km^2. In the Bundaberg district, 81 sites were surveyed from 22/9/97 to 11/6/98 (survey interval approx. 30 days) covering an area of approximately 810 km^2. Published descriptions of solanaceous weeds indicated that they were commonly found in disturbed situations (cultivated land), roadsides and waste places (Cunningham, 1969; Kleinschmidt and Johnson, 1979; Wilson *et al.*, 1995). However, initial surveys indicated that most solanaceous weeds in the two survey areas occurred in cultivated areas, either within or adjacent to crops (often in tractor furrows), so surveys were generally limited to these areas.

At each survey site, the current crop (if present), its growth stage, and the presence or absence of solanaceous weeds was recorded. If weeds were present, the species and its approximate abundance were recorded. Weeds at each site were examined for the presence of TLM (the sample size was the number of individual plants that a single person could examine in approximately 15 minutes). If TLM was detected at a site, in the form of mined leaves and/or the presence of TLM larvae, one of two methods was adopted: (i) in many cases, weeds were found either as single plants or in small isolated patches (<20m^2) and therefore individual plants were examined for the presence of TLM, or (ii) in situations where weeds were scattered over large areas or were abundant, plants within 10 randomly selected 5 x 5m quadrats were examined and the presence of TLM recorded. Samples of mined leaves were collected and taken back to the laboratory where larvae were reared to determine the presence of parasitoids (see below). Solanaceous crops within the survey site were also briefly checked for evidence of TLM infestation. When the identity of a weed was uncertain, plant material was collected and identified by the Herbarium at the Queensland Department of Primary Industries, Indooroopilly.

Mined leaves containing TLM larvae collected from survey sites were placed onto potatoes in the laboratory to provide a food source for developing larvae. The number of TLM adults, and the number and species of parasitoids that emerged was recorded.

2.2 Temperature/development relationship for TLM larvae

2.2.1 Insect rearing

TLM pupae were originally obtained from a colony maintained by Iain Kay at Queensland Department of Primary Industries, Bundaberg.

Larvae were reared on potatoes within plastic containers (10 x 10cm). When larvae were ready to pupate, they dropped to the bottom of the container that was lined with a 1cm layer of coarse sand which larvae used to construct a pupal case. Pupal cases (containing individual pupae) were collected and placed into another container (10 x 10cm, approximately 50 pupae per container) for adult emergence. The container was covered with fine mesh, onto which several drops of honey were placed as food for adults. When adults had emerged, a piece of filter paper (9cm diameter) was placed on top of the mesh to provide a favourable surface for females to lay eggs. The filter paper was removed daily and placed into a petri dish (9cm diameter), sealed with parafilm, and incubated at 27°C until the eggs were close to hatching. The filter paper was then removed and placed onto a potato which provided food for hatching larvae (container described above).

2.2.2 Plant preparation, larval placement, and monitoring

Tomato plants, *Lycopersicon esculentum* var. Roma, were grown in 30 cm pots under glasshouse conditions at Queensland Department of Primary Industries, Indooroopilly until they were approximately 100-120cm high (equivalent to 18 weeks after germination). Two days prior to use in the temperature/development study, the plants were relocated outside to the experimental site at QDPI to allow them to acclimatise to environmental conditions. A total of 15 plants were used in each experiment, arranged into 3 rows of 5 plants, with 50cm between plants within rows, and 150cm between rows. The 5 plants in the middle row were the experimental plants that were infested with TLM larvae. The 10 plants in the outer 2 rows were used as shields or 'windbreaks' for the experimental plants, since under normal field conditions, movement of air would be limited by the arrangement of tomato plants into rows.

The 5 experimental plants were divided into 3 levels based on height. Each plant was approximately 120cm high (from base of plant to top leaves), and therefore each level – lower, middle, and upper – covered approximately 35-40cms. Within each level, 10 leaflets were tagged with coloured tape and numbered to enable easy identification of individual larvae over time. Two data loggers (Micropower Data Logger Model 3, Tain Electronics Pty Ltd, Victoria) were used to record air temperature at 5 different levels in the plant canopy, at 30 minute intervals over the larval development period. Temperature probes were placed at 120cm from the base of the plant (top of plant), 100cm from base (midway in upper level), 60cm from base (midway in middle level), 20cm from base (midway in lower level), and 0cm (on top of soil at base of plant). Probes were attached to the wooden stake supporting the tomato plants, and were covered with white paper to protect them from direct exposure to sunlight. The data loggers themselves were enclosed in polystyrene boxes to protect them from heat and rain, with the wires from the probes passing through a hole cut in the side of the boxes (Plate 1). Canopy air temperature was recorded from experimental plants 2 and 4.

A single newly emerged neonate TLM larva from the laboratory culture (see section 2.2.1) was placed onto each leaflet. Care was taken that larvae were placed onto plants early in the morning to ensure maximum exposure to light and warmth to improve establishment and reduce larval mortality, and to try to select days that would also favour larval establishment (i.e. no rainfall, low wind speed). Every 24 hours the developmental stage of each larva was recorded as well as any mortality ('mortality' included larvae that could not be located after placement on the leaflet). Measurements continued until larvae pupated within the leaf mine or were no longer found in the leaf mine. It is likely that TLM larvae that develop on tomatoes under field conditions pupate in leaf matter found around the base of plants (above

Plate 1. Arrangement of plants, data loggers, and probes to determine the temperature/development relationship for TLM larvae. Data loggers were protected in polystyrene boxes, and individual probes were covered with white paper to prevent direct exposure to sunlight. Leaflets on which larvae were placed were tied with tape for easy identification, with the 3 colours representing the 3 levels within the plant canopy.

the plastic), and therefore it was very difficult to trace the movement of late 4^{th} instar larvae if they moved out of the leaf mine to pupate.

Two experiments were carried out. Data were collected between 18 April – 11 May 1998 in the first experiment, and between 20 May – 22 June 1998 for the second.

2.3 TLM simulation model

This section describes the parameters used to construct the TLM simulation model. It has been written in such a way that this information, together with the 'DYMEX Simulator User Guide', will enable the user to repeat the simulations described here and to perform further simulations to their specifications. The software program, DYMEX Simulator, will be commercially available through CSIRO Publishing (03) 9662 7500) by mid-1999.

The TLM model is made up of a group of modules (Figure 1), which consists of a main TLM lifecycle module and a number of associated modules that influence the population dynamics of TLM within the lifecycle module. Using the DYMEX Simulator, the user can examine the population dynamics of TLM under a range of climatic conditions, crop management practices, and crop hygiene levels. To run the model, the user must first 'initialise' or set the criteria within each of the modules. The following describes the method for initialising each module and how the parameters used in each were derived.

2.3.1 Opening and initialising the TLM model

Within the DYMEX Simulator (dxsimx.exe), open the TLM model file 'leafmine.gmd'. A 'Model description' window will be displayed describing the model and some notes on initialisation of the model. The notes are to remind the user to ensure that the described conditions are correctly set before running the model. Click 'OK' and the 'Model components' window will display the individual modules that make up the model. To initialise a module, click on its icon and select 'Initialise Module'. To obtain more information about the module, such as its input and output variables (i.e. what variables drive that module, and what variables it produces that are used to drive other modules), select 'Module Information'.

2.3.1.1 'Timer' module

The date from which the simulations begin and the length of the simulation from that point can be set. The starting date and the length of the simulation must be within the time length of the meteorological data file being used (see next section). The 'Met Data' module has to be initialised first in order for the start date of the meteorological data file to appear automatically in the start window. The timestep used in the simulations is 1 day, and this cannot be altered by the user from within the DYMEX Simulator.

2.3.1.2 'Met Data (Data File)' module

Meteorological data files used in this module must contain daily maximum and minimum temperature, rainfall, and the date. This information is used to drive the development and mortality of the various TLM life stages. A data file can be selected using the 'Browse'

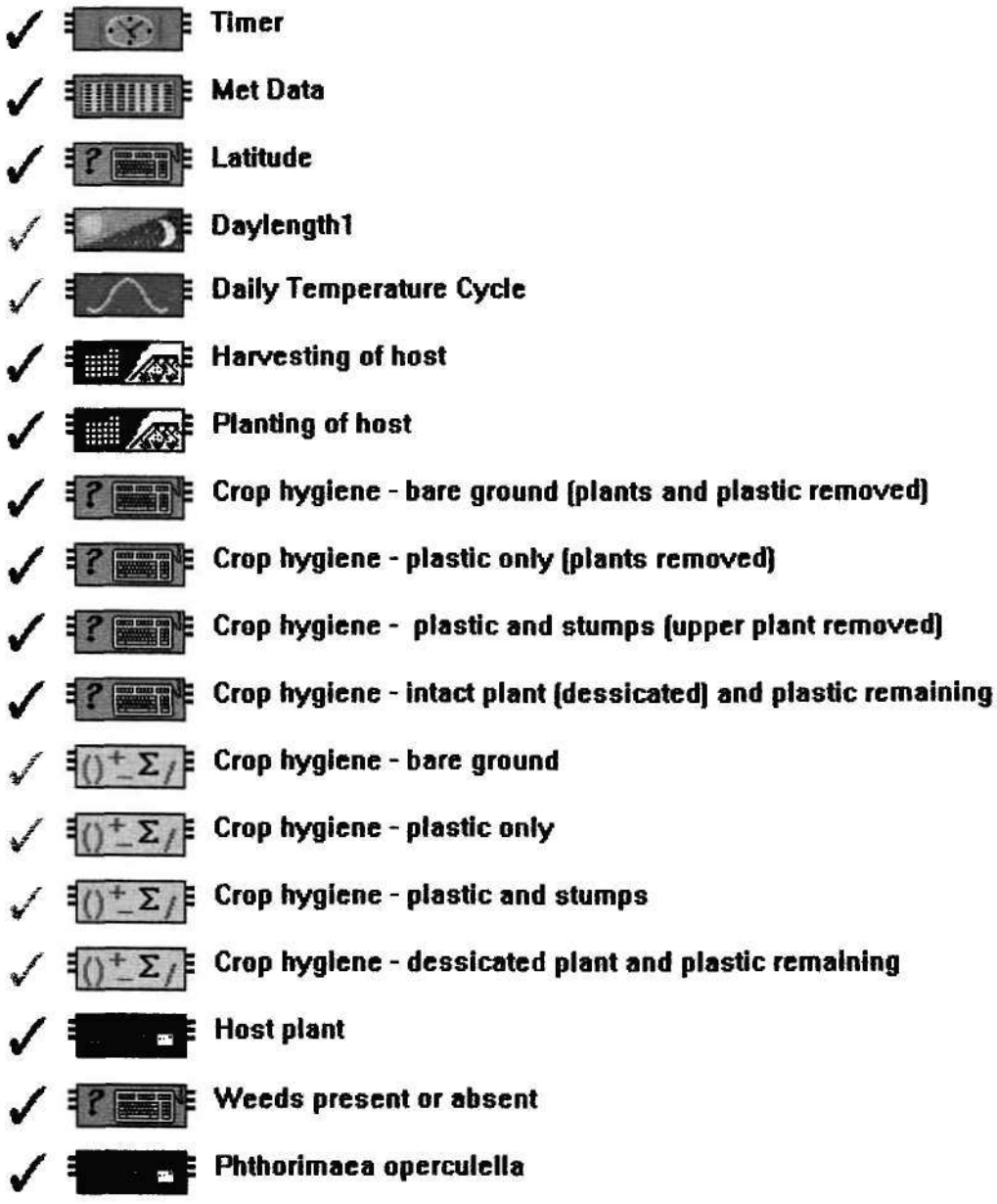

Figure 1. Modules of the TLM simulation model.

button if the required file is not automatically shown. Once selected, the file must be correctly formatted (click 'Format'). The starting column for each of the variables must be specified and this can be done either by highlighting the column with the mouse or by typing in the values. For the meteorological data file from Bundaberg (bundymet.prn) the required format is:

Variable	Start column	Width
minimum temperature	11	4
maximum temperature	17	4
rainfall	22	5

Ensure that the format of the date is correct and that the number of lines in the file header are correct for the particular file being used.

The output variables for this module are maximum and minimum temperature which drives the 'Daily Temperature Cycle' module and influences TLM mortality, and rainfall which also affects TLM mortality.

2.3.1.3 'Latitude', 'Daylength', and 'Daily Temperature Cycle' modules

The user is able to specify the latitude of the geographical region used in the simulation by typing in the value. This information, along with the day of the year (from the 'Timer' module), is used to calculate day length for that region. This in turn is used to generate a daily temperature cycle based on the minimum and maximum temperature. The daily temperature cycle drives temperature-dependent development and mortality in the TLM lifecycle. The 'Daylength' module and 'Daily Temperature Cycle' module do not need to be initialised by the user.

2.3.1.4 'Planting of host' and 'Harvesting of host' modules

These two modules use information from the timer module and allow the user to specify the date on which a tomato crop is planted and when it is harvested. Although harvesting of a tomato crop usually occurs over several weeks in the field, the model only allows the user to enter a single harvesting date, and it is assumed that all fruit is harvested on that date.

To initialise these events, select one event then select 'Add date'. Select the required day and month of the event. More than one date can be added for each event to simulate replanting and harvesting of subsequent crops. In this way the user can choose how soon after one event they would like another event to occur, for example, how soon after harvesting of the first crop the second crop is planted.

When clicking on the icon of one of these event modules the user will note an additional option, the 'Show parameters' option. When this option is selected a window that displays all of the parameters of the model is displayed, and the parameters for this particular module are highlighted. For these particular events, the parameter value will always be 1 as the events are merely acting as 'switches' to trigger other modules. Information from these two modules is used to drive the host plant lifecycle which itself affects the TLM lifecycle. Information from the 'Harvesting of host' module triggers one of the post-harvest 'Crop hygiene' modules, which can be selected by the user (see below) and determines the level of TLM mortality caused by the post-harvest method used.

2.3.1.5 'Crop hygiene (QueryUser)' modules

The work of Baynes (1996) showed that post-harvest crop hygiene significantly affected TLM mortality and therefore the number of moths that continue to emerge following a particular treatment. Four different post-harvest treatments can be simulated in the TLM model: 'bare ground' in which all plant material and plastic mulch are removed following harvest; 'plastic only' where all plant material is removed but the plastic mulch remains; 'plastic and stumps' where the aerial parts of the plant is removed and the plant stump and plastic mulch remains; and 'intact plant' in which the plant and plastic mulch is left intact, although the plant will have been desiccated using a herbicide. The user can select one of the post-harvest crop hygiene treatments by clicking on the icon of the treatment they wish to simulate and selecting 'Initialise module'. The value of that variable should be set at 1. The user must then ensure that all of the other 'Crop hygiene' modules are initialised with 0. This is because it is possible to have more than one of these modules operating at once which may give misleading results in simulations.

When one of the post-harvest crop hygiene treatments is selected, the corresponding 'Crop hygiene (Expression)' module is initialised. These expressions determine the amount of mortality that occurs in each of the lifestages in the '*Phthorimaea operculella* (Lifecycle)' module.

2.3.1.6 'Crop hygiene (Expression)' modules

These modules use the harvesting event and the level of post-harvest crop hygiene selected by the user, to determine the level of mortality that occurs in the various lifestages of TLM following harvesting of the host plant. Detailed research on the effect of post-harvest crop hygiene treatments on survival of each of the lifestages of TLM is needed. In the absence of this detailed information, the initial values for the mortality parameters used in the model were estimated from the level of moth emergence recorded in emergence traps following each of the post-harvest crop hygiene treatments as described in the work of Baynes (1996) (Table 1).

Table 1. Mortality levels imposed on each lifestage of TLM for each post-harvest crop hygiene treatment.

	Mortality (%)			
Post-harvest treatment	eggs	larvae	pupae	adults
bare ground	100	100	100	20
plastic only	100	100	70	20
plastic and stumps	100	90	70	20
intact plant	100	80	60	20

On the date of harvesting of the host plant, insects present (if any) in each lifestage will be subjected to the appropriate mortality level for a particular treatment, thereby affecting the total number of individuals present in that lifestage from that point onwards.

2.3.1.7 'Host plant (Lifecycle)' module

The presence of the host plant is obviously dependent on the planting and harvesting date provided by the user in those respective modules. Despite the apparent complexity of this module, the model assumes that the host plant is always present at the beginning of the simulation and therefore the user need only initialise the 'Host present' lifestage with 1 individual at the start of the simulation. On the harvesting date, the model is designed to 'switch' to the 'Host absent' lifestage. The two outputs, 'Host present' and 'Host absent', are used to drive the establishment mortality of TLM eggs when subsequent crops are planted following the first harvest, and to drive movement of adult TLM to and from weeds if they are present.

2.3.*1.8 'Weeds present or absent (QueryUser)' module*

The presence of solanaceous weeds within or around a current tomato crop may have an important effect on the size of the local TLM population following harvesting of the crop. The user is able to simulate the presence or absence of solanaceous weeds, and thereby examine the effect on TLM numbers. If weeds are present, adult TLM that survive harvest transfer to the weeds until a second crop is planted at which stage they move back. The module is initialised by setting weeds as absent (=0) or present (=1). It would be useful to develop the model further to enable the user to estimate the proportion of weeds present relative to the crop size, which could in turn be used to more accurately predict the surviving TLM population on the weeds.

2.3.1.9 Phthorimaea operculella *(Lifecycle)' module*

The lifecycle module for *Phthorimaea operculella* (TLM) contains all of the functions representing development, mortality, and reproduction for each of the lifestages on host plants. The module also simulates movement of adult TLM from tomato plants to weeds (if present) after harvesting, and immigration of new adults following a planting event. One of the options given in DYMEX when clicking on the TLM lifecycle icon is to 'Toggle lifecycle diagram'. Upon doing this, the lifecycle diagram displayed by DYMEX appears to be incomplete, and in some parts, illogical. This is because in order to simulate movement of insects from host plants to weeds, and immigration, several 'dummy' parameters have been used in the model which affect the lifecycle diagram. The use of these parameters will be described in the sections to follow. An accurate representation of the TLM lifecycle diagram is given in Figure 2. The lifecycle consists of an egg, larval, pupal, and adult stage on tomato plants. Movement of adults from tomato plants to weeds (if present) following a harvesting event, and from weeds to tomatoes following a planting event is also represented.

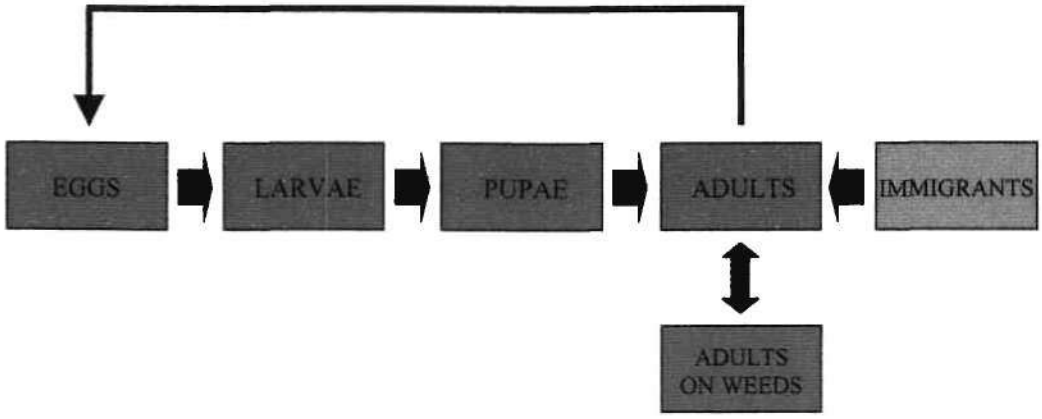

Figure 2. DYMEX lifecycle diagram for *Phthorimaea operculella*. Blue boxes represent insects on tomato plants. Green box represents insects on weeds (if present) in the absence of tomato hosts. Red box represents immigrants from an independent and possibly unknown source.

Wherever possible, parameters used in functions that describe TLM development, mortality and reproduction are derived from published data. There are relatively few ecological investigations of TLM, and of those that exist, there is great variation in the methodology thereby making comparisons difficult. For most parameters, values have been selected based on the published results of only one or two studies to maintain some level of consistency. The user may vary most parameter values, particularly if information becomes available from a single, local ecological study. Similar parameters are used in most lifestages of TLM on tomatoes, therefore only a general description of the derivation of the value and use of the parameter will be given. Parameters for TLM adults on weeds and immigrant stages will be described separately.

TLM ON TOMATOES

Insects in each lifestage are subjected to two types of mortality: establishment and continuous. Establishment mortality occurs at a single timestep as insects are transferred from one lifestage to the next, whereas continuous mortality can occur throughout the lifestage.

Establishment mortality in this model is used to represent 'miscellaneous' mortality that can occur within a lifestage, other than that caused by low or high temperatures and rainfall. Such mortality may include egg infertility, or diseased or 'unfit' larvae. Values used in the model were estimates derived from studies by Foot (1979) and Briese (1986).

Continuous mortality in each lifestage occurs when temperatures become extreme, or when rainfall is high. Temperature dependent mortality is driven either by a linear above threshold (for high temperatures) or linear below threshold (for low temperatures) function. Published threshold levels for TLM vary (Broodryk, 1971; Briese, 1980; Rothschild, 1986) and therefore the level used in the model is an approximation based on this data. Estimated values are used for the rate of mortality above or below these thresholds as no published data exists. However, some studies have indicated that the rate of mortality of TLM above the upper

temperature threshold would be very high (Broodryk, 1971; Briese, 1980). The rate of mortality at low temperatures is less clear, and has currently been set relatively conservatively. When a simulation is run that uses a meteorological data base that contains several days where the temperature is above or below the set threshold levels, extinction of the population may occur (which is unlikely to happen under field conditions). In these cases, the rate of mortality may have to be decreased slightly to prevent a population crash.

Whether rainfall causes significant mortality in TLM populations on tomato plants is unknown. Direct effects of rainfall are most likely to be on adults, and larvae that are not protected within a mine (Rothschild, 1986). Studies that have considered rainfall have focussed on TLM populations on potato tubers and therefore the indirect effect of rainfall on soil moisture and hence on TLM larvae (Foot, 1979). Mortality due to rainfall operates as a step function in the model, where a specified level of mortality occurs whenever daily rainfall is above the threshold.

In the adult lifestage on tomatoes, there is no establishment mortality. To more accurately reflect field conditions, mortality occurs at a low level on a daily basis, until adults reach a particular chronological age, in this case 18 days after emergence (based on Briese, 1980), at which point they all die. The estimate of adult longevity is based on data from several sources (Graf, 1917; Rothschild, 1986; Hargreaves, 1992).

With the exception of adults, development in each stage is influenced by the daily temperature cycle and is driven by a linear above threshold function which increases the physiological age of the insect. Data for the temperature threshold above which development occurs, and the rate of development above that temperature are derived from extrapolation of the values published by Broodryk (1971). Once the physiological age of a cohort of insects reaches 0.9, they transfer to the next stage.

Transfer of insects from one stage to the next is also driven by a linear above threshold function with a specified threshold age and rate of transfer. This is designed to simulate gradual transfer of insects from one stage to the next over several timesteps rather than all insects transferring in a single timestep.

Adult reproduction is modeled as a simple step function where adult females lay a specified number of eggs at a particular chronological age. Again, published levels of fecundity for TLM are highly variable ranging from approximately 40-290 eggs per female (Rothschild, 1986). Based on studies of progeny production (i.e. actual number of eggs laid) (Foot, 1979; Briese, 1980), the average number of eggs laid per female was estimated to be 150. This number was divided by 2 to account for a 1:1 sex ratio in the adult population. Eggs are laid by females 2 days after emergence.

ADULT TLM ON WEEDS

TLM adults that transfer onto weed hosts (if present) following a harvesting event are subjected to an establishment mortality and continuous mortality driven by temperature and rainfall. The values for these parameter are the same as those set for adults on tomato plants.

Simulation of a complete lifecycle for TLM on weeds to include development and reproduction has not been developed. This was because to date, nothing is known about these processes on solanaceous weeds. However, the work of Ford (1998) indicated that

development and reproduction of TLM on weeds may vary substantially from what is known to occur on solanaceous crops. As this information becomes known, processes of development and reproduction on weeds can easily be incorporated into the model to more accurately simulate the impact of weeds on TLM populations.

IMMIGRANTS

There are only two parameters for immigrating TLM adults: fecundity and progeny production. In this model, immigrant fecundity has no direct effect on the TLM population. Its value is set to an extremely high level to ensure that when a tomato crop is planted, there will always be an immigrating population. The size of that population is determined by the level of progeny production set by the user. Progeny production has been defined as a linear function so that immigration can occur over several timesteps (i.e. adults can immigrate into a new planting over a period of several days) rather than in a single timestep (i.e. a single influx on one day).

The '*Phthorimaea operculella* (Lifecycle)' module is initialised by specifying the number of individuals (in any lifestage) to add to the simulation on a particular date. The same number of individuals can be added again at regular intervals that can be designated by the user by specifying the number of repeats and the time interval (in days).

This module produces a large number of output variables, such as the total number of individuals in each lifestage, their average physiological age, and their development time, which can then be used to graph or tabulate the simulation results.

2.3.2 Running a simulation

When the modules have been initialised and the parameters set to the required values by the user, a simulation can be run using the 'Execution/Run' menu. A 'run identifier' can be used to identify individual simulations. The simulation period is set by the information given in the 'Timer' module, however, changes can be made at this point.

Once the simulation has run a results window will be displayed and a 'Results' menu will appear. Results can be viewed in tabular or graphical form. The user can select the variables of interest to appear in the table or chart.

2.3.3 Case studies

The simulation model was used to predict TLM population patterns under several different crop management regimes. Descriptions of the types of variables and parameters used are given together with the results in the 'Results' section to avoid switching back and forth between sections. Simulations examined the effect of crop hygiene strategies on post-harvest TLM populations in both the presence and absence of solanaceous weeds; the effect of continuous planting versus a production break in the presence and absence of weeds; and what constitutes an 'effective' production break in tropical tomato growing regions such as Bundaberg and Bowen, and in more temperate climates such as the Lockyer Valley and Victoria.

3.0 Results

3.1 Alternative host plant survey

3.1.1 Lockyer Valley district

Six species of weeds from the family Solanaceae and one from Amaranthaceae that could act as potential hosts to TLM were found in cultivated areas in the Lockyer Valley (Table 2).

Table 2. Occurrence of weeds at 39 sites surveyed in the Lockyer Valley district from 28/11/96 to 23/1/98, and the frequency of TLM infestations.

Scientific name (Family Solanaceae unless indicated)	Common name	Number of sites found (% of total sites)	Number of TLM infestations
Solanum nigrum	Blackberry nightshade	20 (51.3)	3
Cestrum parqui	Green cestrum	9 (23.1)	0
Amaranthus dubies†	Green amaranth	8 (20.5)	0
Datura ferox	Datura	4 (10.3)	0
Nicandra physalodes	Apple of Peru	4 (10.3)	1
Datura stramonium	Common thornapple	3 (7.7)	2
Solanum americanum	Glossy nightshade	2 (5.1)	0

†Family Amaranthaceae

Blackberry nightshade was by far the most common solanaceous weed found in the area, occurring at over 50% of surveyed sites and throughout the whole survey period. It was usually found scattered either throughout a crop or recently disturbed land (harvested, ploughed in or rotary hoed), however on one occasion it was present in a thick stand measuring approximately 1m x 50m.

Unlike the other weeds, green cestrum was only ever found at sites where the current or recently harvested crop was adjacent to a creek bank, and plants were found lining the bank. Most plants were very mature, measuring up to 3m in height. Like blackberry nightshade, these plants were recorded throughout the survey period.

While not a member of the Solanaceae, green amaranth was included in the survey as it had previously been recorded as a host plant of TLM (Das and Raman, 1994). Green amaranth was commonly found lining the edge of crops and scattered within. It was only recorded at sites between August and December 1997.

The occurrence of *Datura ferox* was very patchy both within crops and over time. It was only recorded in April, July and December 1997, and only as a few plants scattered within the crop. Similarly, Apple of Peru was patchily distributed in July and October 1997. However, in December 1997, dense coverage with this plant was recorded at two sites, with many mature plants (height approx. 1.5m) going to seed.

Datura stramonium, or the common thornapple, was found to be abundant at 3 sites between October and December 1997, but was not recorded at other times during the survey period.

Glossy nightshade was the least abundant of the solanaceous weeds, occurring at only 2 sites throughout the survey period. In both cases, plants were found scattered at rare intervals along crop edges.

Only 3 of the solanaceous weed species showed evidence of TLM infestation – blackberry nightshade, Apple of Peru, and the common thornapple. All infestations were recorded on one survey date (30/10/97) and at total of 3 survey sites.

The first site was a recently harvested block in which green amaranth, potato volunteers, and blackberry nightshade were recorded (approx. relative density 26:13:1). Most of the potato volunteers had leaves that were mined by TLM larvae, and TLM adults were observed while walking through the block. A total of 4 blackberry nightshade plants were infested with TLM larvae, although many of the mines were empty. No TLM infestation was found on green amaranth.

The second site was a current potato crop (prior to harvest) with green amaranth, blackberry nightshade, and common thornapple scattered between rows (approx. relative density 170:30:1). The potatoes were infested with TLM. Every common thornapple plant had multiple leaves mined by TLM larvae, while only 3 blackberry nightshade plants were infested.

A similar situation occurred at the third site, a harvested potato block, however the weed density was so great at this site that it was not possible to move through the block to obtain a good estimate of relative weed density. The common thornapple was the most abundant species, with green amaranth, blackberry nightshade, and Apple of Peru scattered throughout. Again, every common thornapple plant was infested with TLM larvae, while fewer than 5% of Apple of Peru were infested, and only a single blackberry nightshade plant was infested.

One important feature noted when examining plants that were infested with TLM larvae was that the mines found on leaves of blackberry nightshade and Apple of Peru were always small and often contained very small leafminer larvae (1st instars) or no larvae at all.

On two other occasions, TLM infestations were noted – one in a current potato crop, and another in a recently harvested potato block where infested potato tubers were found on the surface. In the first case, green amaranth was found throughout the crop but was not infested by TLM. In the latter case, blackberry nightshade was scattered over the block, and no evidence of TLM infestation was found.

Rearing of field collected larvae on potato in the laboratory revealed that parasitism of TLM larvae developing on solanaceous weeds could occur. Levels of parasitism of TLM larvae developing on each species was not determined and is outside the scope of this research. Adult parasitoids emerging from TLM larvae collected from common thornapple included the braconid wasps *Orgilus lepidus* Muesbeck and *Apanteles subandinus* Blanchard, and the encyrtid wasp *Copidosoma desantisi* Annecke and Mynhardt. *O. lepidus* emerged from TLM collected from blackberry nightshade, while no parasitoids emerged from larvae collected on Apple of Peru.

3.1.2 Bundaberg district

Seven species of weeds from the family Solanaceae and one from Amaranthaceae that could act as potential hosts to TLM were found in cultivated areas in the Bundaberg district (Table 3).

Table 3. Occurrence of weeds at 81 sites surveyed in the Bundaberg district from 22/9/97 to 11/6/98, and the frequency of TLM infestations.

Scientific name (Family Solanaceae unless indicated)	Common name	Number of sites found (% of total sites)	Number of TLM infestations
Solanum nigrum	Blackberry nightshade	47 (58.0)	1
Amaranthus dubies†	Green amaranth	42 (51.9)	0
Solanum torvum	Devil's fig	14 (17.3)	2
Solanum americanum	Glossy nightshade	13 (16.0)	0
Physalis minima	Wild gooseberry	6 (7.4)	0
Physalis ixiocarpa	Annual ground cherry	5 (6.2)	3
Datura stramonium	Common thornapple	5 (6.2)	1
Datura ferox	Datura	2 (2.5)	2

†Family Amaranthaceae

As was the case in the Lockyer Valley district, blackberry nightshade was the most common solanaceous weed at the surveyed sites in the Bundaberg district. Blackberry nightshade, along with glossy nightshade and green amaranth was found scattered between rows of tomato blocks and around crop edges throughout the survey period. One large stand of blackberry nightshade (approx. 1m x 400m) that extended along the edge of a harvested tomato block was recorded at one survey site.

Other weeds species recorded in the Bundaberg area were found only at particular times during the survey period, and were most commonly scattered throughout a block or in small isolated patches. *Solanum torvum*, or Devil's fig, was recorded at survey sites from November 1997 through until June 1998; wild gooseberry and annual ground cherry were found between March and June 1998; common thornapple was found in September and October 1997; and *Datura ferox* was found at only 2 sites in February 1998.

Five of the eight weed species recorded in the Bundaberg district were infested with TLM larvae at some stage during the survey period. However, each of these infestations was recorded at a separate site (with one exception), and in many cases, only a small number of individual plants were affected.

Annual ground cherry was most commonly infested with TLM larvae, with 3 infestations recorded out of the 5 sites at which it was found. In all 3 cases, ground cherry plants were scattered throughout tomato blocks, and in each of the blocks, the following levels of infestation were found: block 1 – 2/18 plants infested, block 2 – 1/40 plants infested, block 3 – 8/23 plants infested (numbers provided are the total number of plants found in 10 5 x 5m quadrats). Block 3, in which the highest level of infestation was found, was a mature tomato

block that was being picked for the last time on the day of the survey. The single record of TLM infestation on blackberry nightshade also occurred in this block. The level of infestation of blackberry nightshade was 1/51 plants. The single plant that was infested was found growing into a tomato bush that was infested with TLM larvae, however the bush was in very poor condition. Many of the mines found on the leaves of the blackberry nightshade were empty and most were very small, although larval frass (faeces) was noted in some of the mines indicating the relatively recent presence of TLM larvae.

Datura ferox was found at only 2 sites during the entire survey period. In both cases, the plants were found in a harvested potato block that had been ploughed in, and in both cases, plants were infested with TLM larvae. At the first site only a single plant was found and at the second site, a patch of 25 plants was recorded, and 22/25 plants were infested with TLM larvae.

Similarly, Devil's Fig was also infested with TLM larvae at 2 sites. At one site, plants were scattered unevenly throughout a capsicum block in which plants had been desiccated. An inspection of 10 randomly selected Devil's Fig showed 60% infestation with TLM. At a second site, a single infested plant was found adjacent to a block of tomatoes that was also infested with TLM.

A single stand of common thornapple measuring approximately 2 x 5m was found to be heavily infested with TLM larvae, with 80% of plants having mined leaves and most possessing multiple mines. This stand of thornapple was found in a ploughed in paddock adjacent to a block that had previously contained tomatoes but now had zucchinis planted into the old tomato plastic. A substantial amount of tomato crop trash was still present.

There were 23 sites where TLM infestation was recorded on solanaceous crops – 18 on tomatoes and 5 on potatoes, but where no evidence of infestation of weeds within or around those crops was found.

A feature that was noted both in Bundaberg and the Lockyer Valley was that leaf mines on the common thornapple ranged substantially in size and larvae of all stages could be found in the mines. Many of the mines found on other weed species were often small and contained only first or second instar larvae.

Rearing of larvae collected from the field sites around Bundaberg suggested that parasitism of TLM larvae in many of these weed species was limited. *A. subandinus* was the only parasitoid species to emerge, with the majority emerging from TLM larvae collected from common thornapple, and a single parasitoid emerging from larvae collected on blackberry nightshade.

3.2 Temperature/development relationship for TLM larvae

Larval 'mortality' was very high in both experiments; 82.3% in experiment 1 and 80.9% in experiment 2. In most cases, no evidence of a leaf mine could be found, suggesting that larvae had wandered off of the leaflet they were placed on or did not attach to the leaflet to start with. Very few larvae were found dead within leaf mines. The use of laboratory reared larvae may have contributed to this high proportion of 'unaccounted for' larvae. These larvae

were not accustomed to large fluctuations in temperature and humidity, and had also been reared on potato for several generations, although larvae used in each experiment had not been provided with a food source since emergence. It is a possibility that rearing on a particular plant species preconditions emerging larvae for that species, thereby affecting the level of establishment when provided with a different (although related) species as a food source. Insect predators, particularly ants, could also account for high mortality levels.

Of the larvae that survived in each experiment, differences in the development time for larvae on each plant and between each level were analysed. In experiment 1, there were no significant differences in the development time of larvae on each of the five plants ($F_{0.05,4}$=0.76, P=0.56), and no significant difference on the time taken for larvae to develop in each level ($F_{0.05,2}$=0.44, P=0.65). The mean development time from neonate larva to the pupal stage was 19.13 days. Similarly, in experiment 2, there were no differences in development time of larvae on different plants ($F_{0.05,4}$=0.42, P=0.80), or between different levels on the plants ($F_{0.05,2}$=0.35, P=0.70). The mean development time for larvae in experiment 2 was 25.0 days.

Analysis of the temperature data from one of the data loggers revealed a fault, therefore data from only one logger could be used in later simulations to calibrate the model (see section 3.3.1). Daily maxima and minima throughout the experiments were calculated from the information collected by the data logger and used to calibrate the model.

3.3 TLM simulation model – calibration and example simulations

3.3.1 Calibration of rate of larval development

Analysis of larval development showed that there was no difference in the rate of development on different plants or at different levels on those plants (see section 3.2), and therefore temperature data from only the probe located at the top of the plant was used to calibrate the model. Examination of temperature data recorded by the data logger revealed that temperature was being recorded every hour rather than every ½ hour, and thus data output had to be manually adjusted. Daily maxima and minima were calculated (as Dymex can only use data in this form) and this data compared to daily maxima and minima recorded at Brisbane airport (obtained from the Bureau of Meteorology, Brisbane) to confirm that the data logger was performing accurately. The overall pattern of temperature fluctuation at the two sites correlated reasonably well (Figure 3), with temperatures at the field site typically 1-3 degrees below those obtained at Brisbane airport.

Data collected from the field site was then used as the meteorological database in a short simulation to calibrate larval development time in the simulation model. Modules were initialised using the settings shown in Table 4, run 1. The larval development period in this simulation was 28 days and therefore longer than the average development time of 25 days recorded in field observations carried out in the same time period (see section 3.2). To adjust the development time in the model to match field observations, the parameter that controls the rate of larval development was altered from 0.005 to 0.0055 (Table 4, run 3), resulting in a larval development period of 25 days.

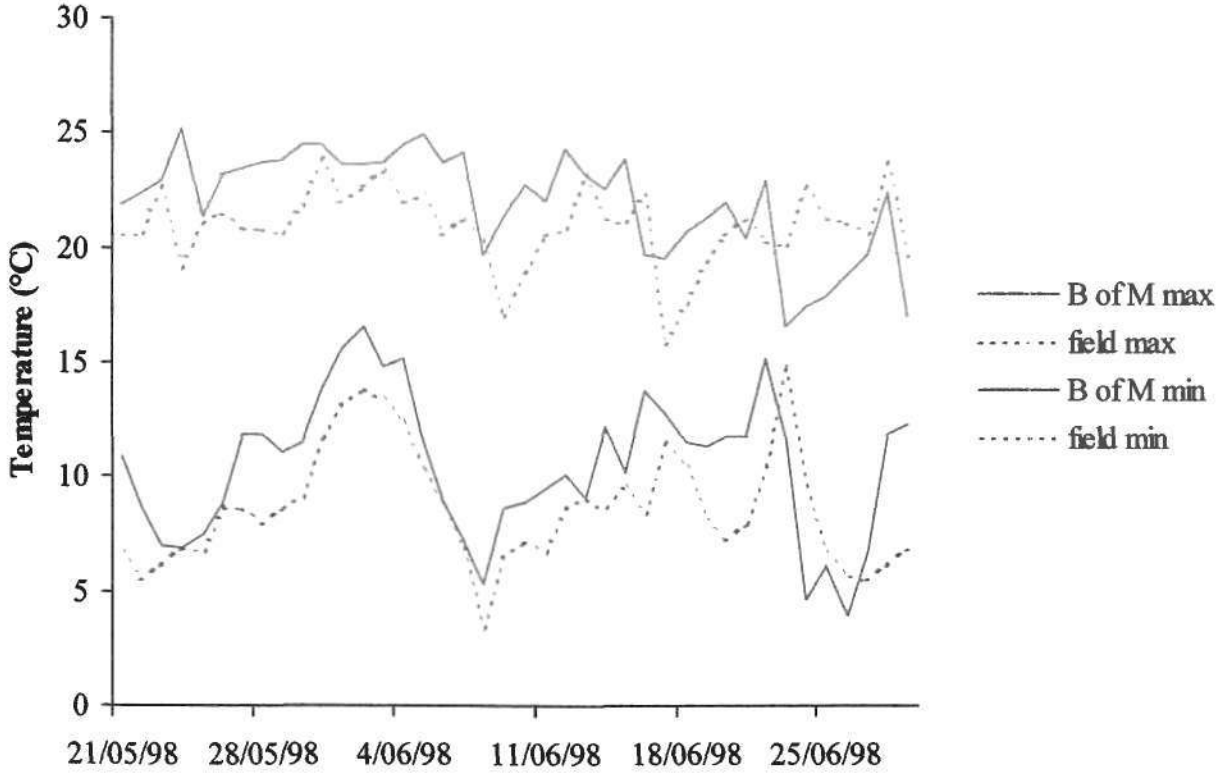

Figure 3. Comparison of daily maxima and minima obtained from the Bureau of Meteorology (B of M), Brisbane and from the data logger located at the field site at QDPI Indooroopilly

Table 4. Run descriptions for TLM simulation model showing user-defined settings used for each run. A short description of the main variation between runs is given under 'Run variation'.

Run	Timer	Met Data	Latitude	Planting	Harvesting	Crop hygiene level	Weeds	TLM	Run variation
1	start 21/5/98 runs 33 days	'field data.prn'	-27.47	21 May	-	4	absent	1000 larvae	
2	start 21/5/98 runs 33 days	'field data.prn'	-27.47	21 May	-	4	absent	1000 larvae	rate of larval development = 0.007
3	start 21/5/98 runs 33 days	'field data.prn'	-27.47	21 May	-	4	absent	1000 larvae	rate of larval development = 0.0055
4	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March	3 August	1	absent	20 adults/day, 7 repeats	
5	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March	3 August	1	absent	20 adults/day, 7 repeats	rate of low temperature mortality for all lifestages decreased from –0.02 to –0.01
6	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March	3 August	2	absent	20 adults/day, 7 repeats	crop hygiene level
7	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March	3 August	3	absent	20 adults/day, 7 repeats	crop hygiene level
8	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March	3 August	4	absent	20 adults/day, 7 repeats	crop hygiene level
9	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March	3 August	1	present	20 adults/day, 7 repeats	weeds present
10	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March	3 August	2	present	20 adults/day, 7 repeats	weeds present, crop hygiene level
11	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March	3 August	3	present	20 adults/day, 7 repeats	weeds present, crop hygiene level
12	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March	3 August	4	present	20 adults/day, 7 repeats	weeds present, crop hygiene level
13	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March 10 August	3 August 21 November	1	absent	20 adults/day, 7 repeats	2nd planting 1 week after 1st planting harvested
14	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March 10 August	3 August 21 November	2	absent	20 adults/day, 7 repeats	2nd planting 1 week after 1st planting harvested, crop hygiene level

Table 4. (cont.)

Run	Timer	Met Data	Latitude	Planting	Harvesting	Crop hygiene level	Weeds	TLM	Run variation
15	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March 10 August	3 August 21 November	3	absent	20 adults/day, 7 repeats	2nd planting 1 week after 1st planting harvested, crop hygiene level
16	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March 10 August	3 August 21 November	4	absent	20 adults/day, 7 repeats	2nd planting 1 week after 1st planting harvested, crop hygiene level
17	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March 31 August	3 August 19 December	1	absent	20 adults/day, 7 repeats	2nd planting 4 weeks after 1st planting harvested
18	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March 31 August	3 August 19 December	2	absent	20 adults/day, 7 repeats	2nd planting 4 weeks after 1st planting harvested, crop hygiene level
19	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March 31 August	3 August 19 December	3	absent	20 adults/day, 7 repeats	2nd planting 4 weeks after 1st planting harvested, crop hygiene level
20	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March 31 August	3 August 19 December	4	absent	20 adults/day, 7 repeats	2nd planting 4 weeks after 1st planting harvested, crop hygiene level
21	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March 31 August	3 August 19 December	2	present	20 adults/day, 7 repeats	2nd planting 4 weeks after 1st planting harvested, weeds present
22	start 24/3/93 runs 365 days	'bundymet.prn'	-24.87	24 March	3 August	1	absent	20 adults/day, 7 repeats	pupal mortality at time of harvest = 0.95
23	start 31/8/93 runs 365 days	'bundymet.prn'	-24.87	31 August	19 December	1	absent	20 adults/day, 7 repeats	tomato crop planted in late spring with planned production break in summer
24	start 31/8/93 runs 365 days	'bundymet.prn'	-24.87	31 August	19 December	2	absent	20 adults/day, 7 repeats	tomato crop planted in late spring with planned production break in summer, crop hygiene level
25	start 31/8/93 runs 365 days	'bundymet.prn'	-24.87	31 August	19 December	3	absent	20 adults/day, 7 repeats	tomato crop planted in late spring with planned production break in summer, crop hygiene level
26	start 31/8/93 runs 365 days	'bundymet.prn'	-24.87	31 August	19 December	4	absent	20 adults/day, 7 repeats	tomato crop planted in late spring with planned production break in summer, crop hygiene level
27	start 25/8/93, runs 365 days	'bowhort.prn'	-20.08	25 August	8 December	1	absent	20 adults/day, 7 repeats	production break in summer in Bowen region
28	start 25/8/93, runs 365 days	'bowhort.prn'	-20.08	25 August	8 December	3	absent	20 adults/day, 7 repeats	production break in summer in Bowen region, crop hygiene level
29	start 14/9/93, runs 365 days	'bowhort.prn'	-20.08	14 September	30 December	1	absent	20 adults/day, 7 repeats	production break 4 weeks later in summer in Bowen region
30	start 13/1/90, runs 365 days	'victoria.prn'	-27.57	13 January	5 May	1	absent	20 adults/day, 7 repeats	summer-autumn tomato production in Victoria

The rate of development for eggs and pupae (0.017 and 0.007 respectively) can also be adjusted to further calibrate the model once information on the temperature/development relationship for these lifestages is obtained.

3.3.2 Example simulations

Simulations were run to examine the effect of different management strategies on TLM in the various regions. The two strategies were crop hygiene and the presence or absence of weed hosts in and around the crop. The effect of crop hygiene was tested firstly on its own, then in combination with the presence/absence of weed hosts.

The effect of crop hygiene on the TLM population was examined using meteorological data and cropping data collected at the Bundaberg Research Station in 1993. Dates for planting and harvesting of the host plant were selected based on cropping data collected by J. Barnes (QDPI, Bundaberg), and the harvesting date used in the simulations was based on the date of the last pick of the crop. Settings used in this simulation are shown in Table 4, runs 4-8.

In the initial run, the TLM population unexpectedly 'crashed' in mid-June. Examination of the meteorological data in this period revealed several consecutive minimum temperatures of 4-5°C. Under field conditions it is unlikely that a short period of low temperatures will kill all insects in all lifestages, suggesting that the rate of low temperature mortality used in the simulation was too high. For future simulations, the rate of low temperature mortality was altered from –0.2 to –0.1 for all lifestages of TLM on the host plant and for adult TLM on weed hosts.

The level of crop hygiene adopted by a grower in the absence of weed hosts can dramatically affect the length of time that a residual TLM population can be found in the vicinity of the crop (Figure 4a-d). At the highest level of crop hygiene, that is, when all plant material and plastic mulch are removed immediately after harvest, TLM adults that survive the treatment can be found in the harvested crop up to 17 days after harvest (mid August). At the next level of crop hygiene where all plant material is removed but the plastic mulch is left, TLM adults can be found in the crop until late August. At the lowest level of crop hygiene where the desiccated plant is left intact and the plastic mulch remains, adults are present in the crop until mid September.

Using the same settings as runs 5-8, further simulations were carried out to assess the impact of the presence of weeds on TLM numbers (Table 4, runs 9-12). The presence of weeds at the time of harvest provides a refuge for emerging TLM adults (Figure 5a). Adults that survive the treatment or emerge at some stage after harvest transfer onto the weed hosts. The level of crop hygiene affects the total number of adults that transfer onto the weeds (Figure 5a-d).

Given that the level of crop hygiene used by a grower can affect the length of the period that adult TLM are present after harvesting, the effect of replanting at different intervals after the first harvest (i.e. the length of the production break) was examined firstly in the absence of weed hosts. Using the settings in runs 5-8, second planting and harvesting events occurring 1 week after the harvesting of the first planting were added to the event schedule (Table 4, runs 13-16). The results show that the second planting was infested immediately with surviving adults from the first planting moving onto the new planting and with infestation from immigrants (Figure 6a). As the level of crop hygiene decreases, the number of adult TLM infesting the new planting increases significantly, populations are larger throughout the

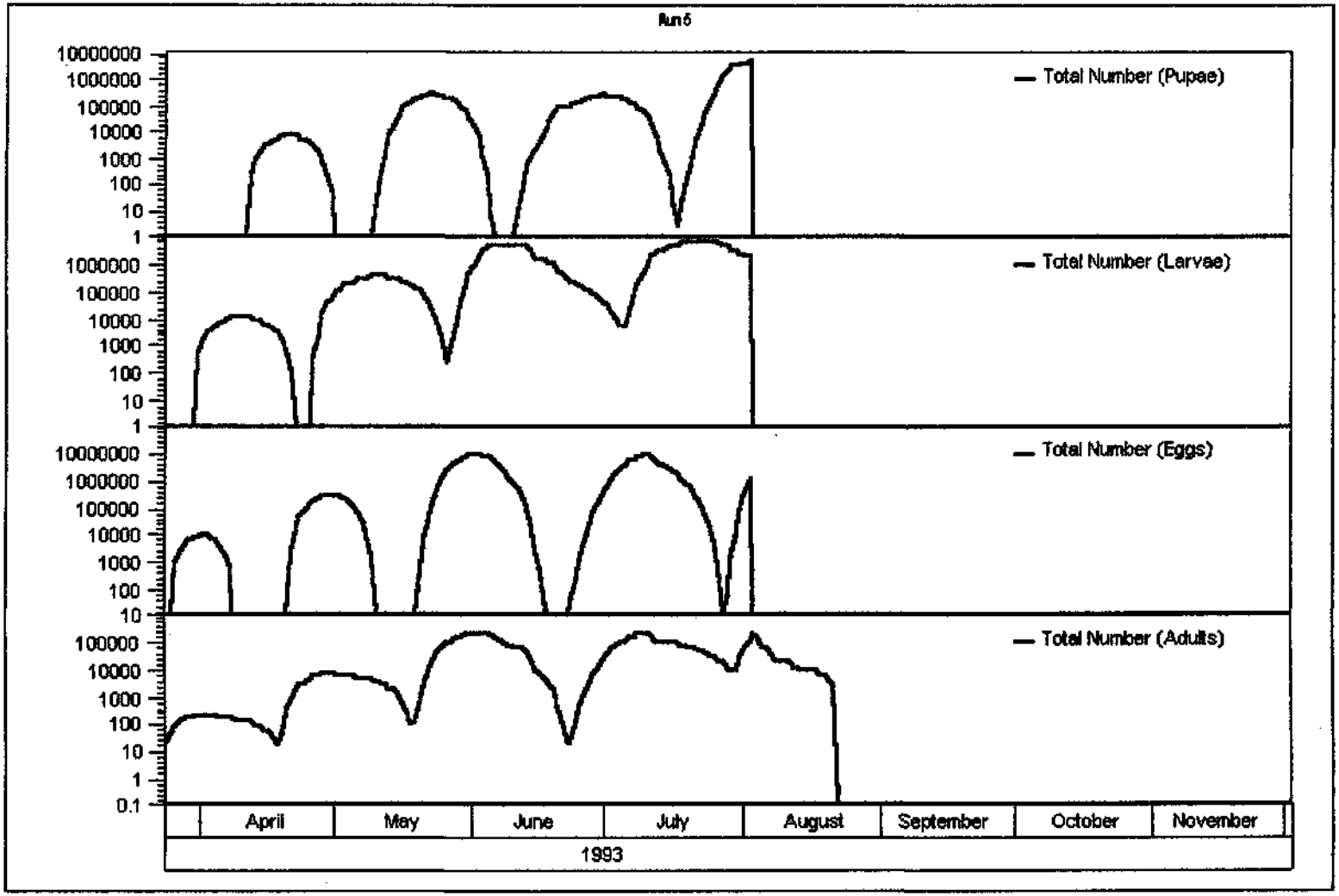

Figure 4a Simulation of a TLM population with post-harvest crop hygiene level set at 'bare ground' (i.e. level 1) in the absence of weeds. Cropping period: 24 March - 3 August.

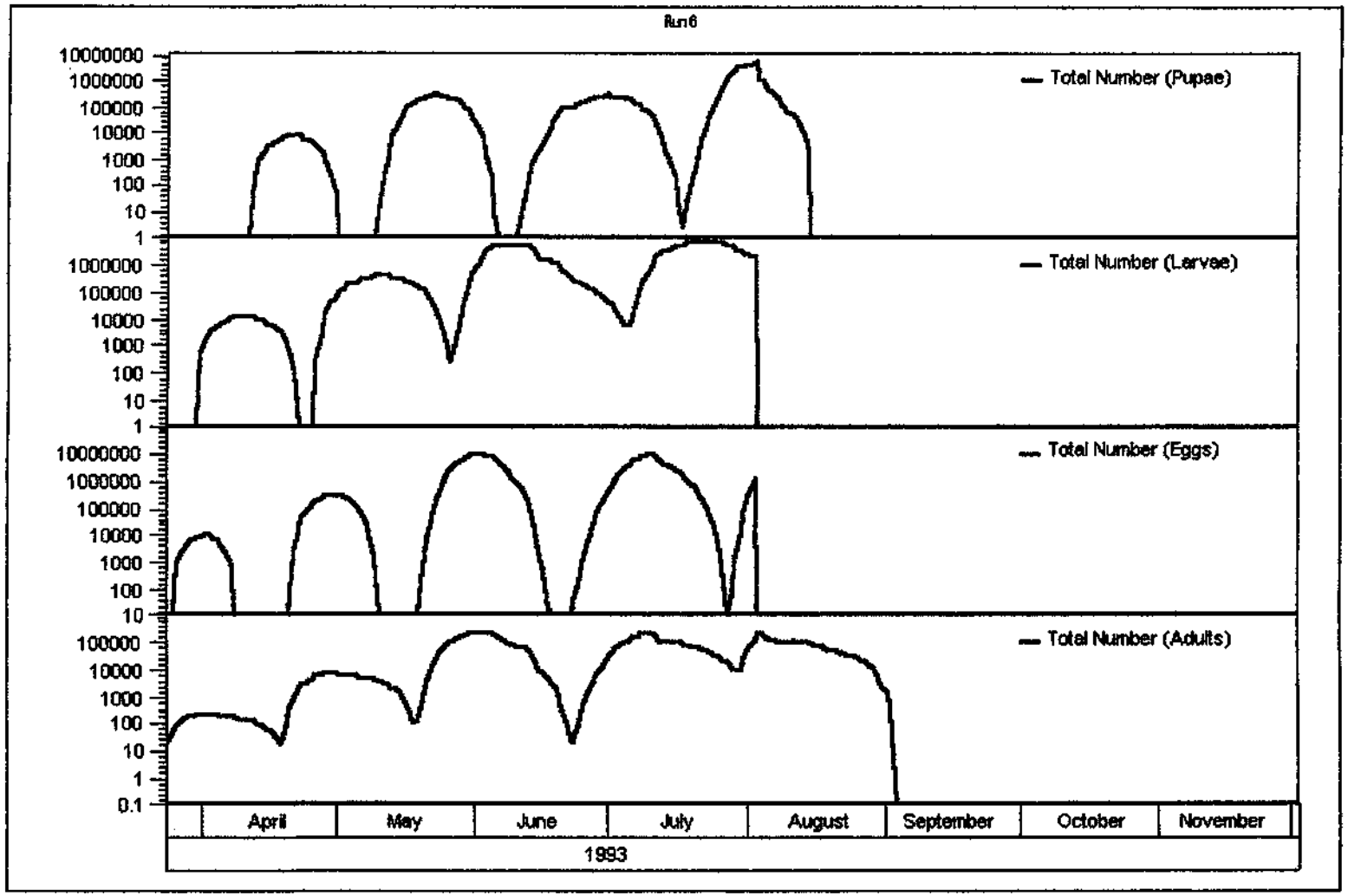

Figure 4b Simulation of a TLM population with post-harvest crop hygiene level set at 'plastic only' (i.e. level 2) in the absence of weeds. Cropping period: 24 March - 3 August.

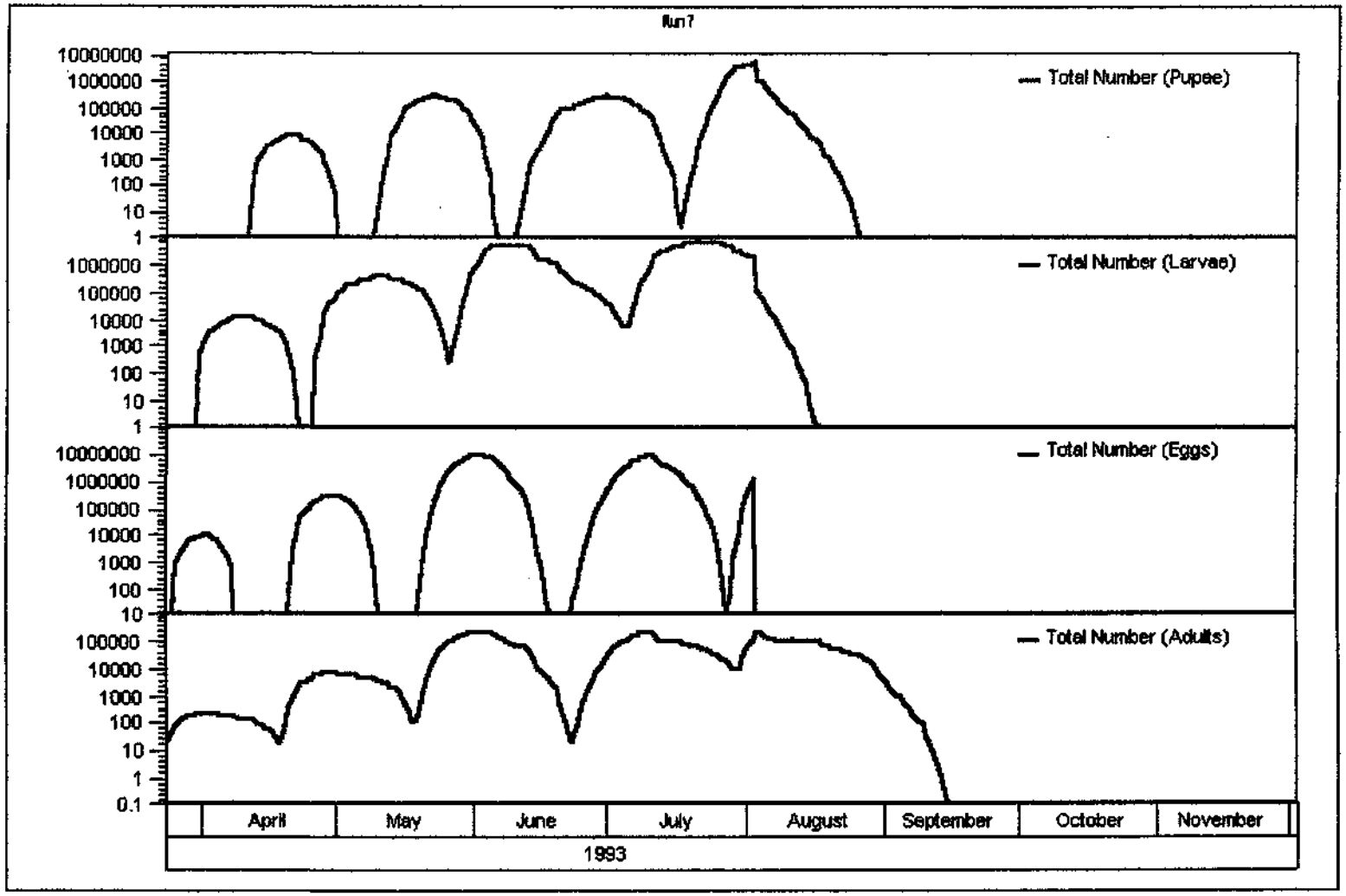

Figure 4c Simulation of a TLM population with post-harvest crop hygiene level set at 'plastic and stumps' (i.e. level 3) in the absence of weeds. Cropping period: 24 March - 3 August.

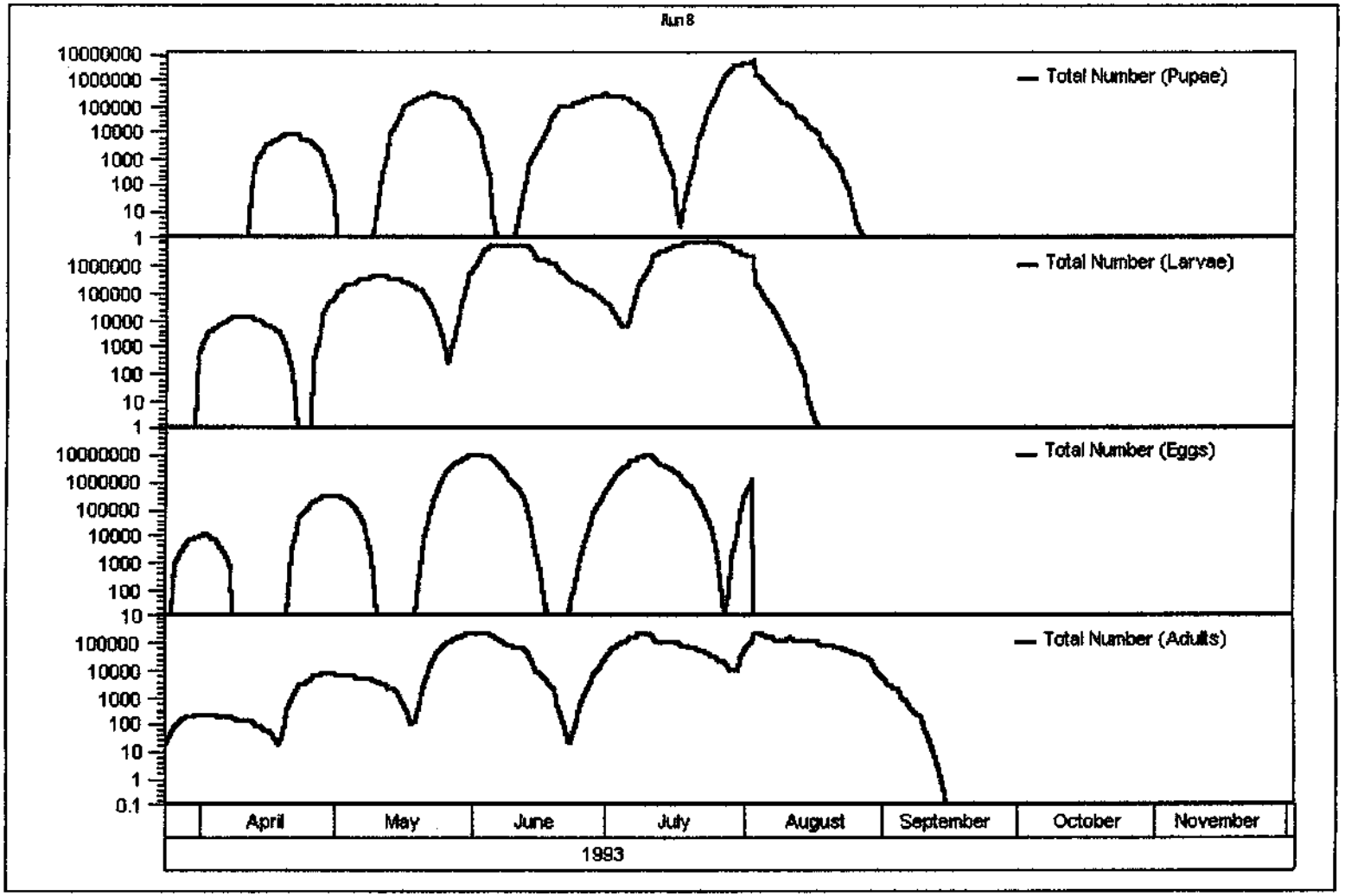

Figure 4d Simulation of a TLM population with post-harvest crop hygiene level set at 'intact plant' (i.e. level 4) in the absence of weeds. Cropping period: 24 March - 3 August.

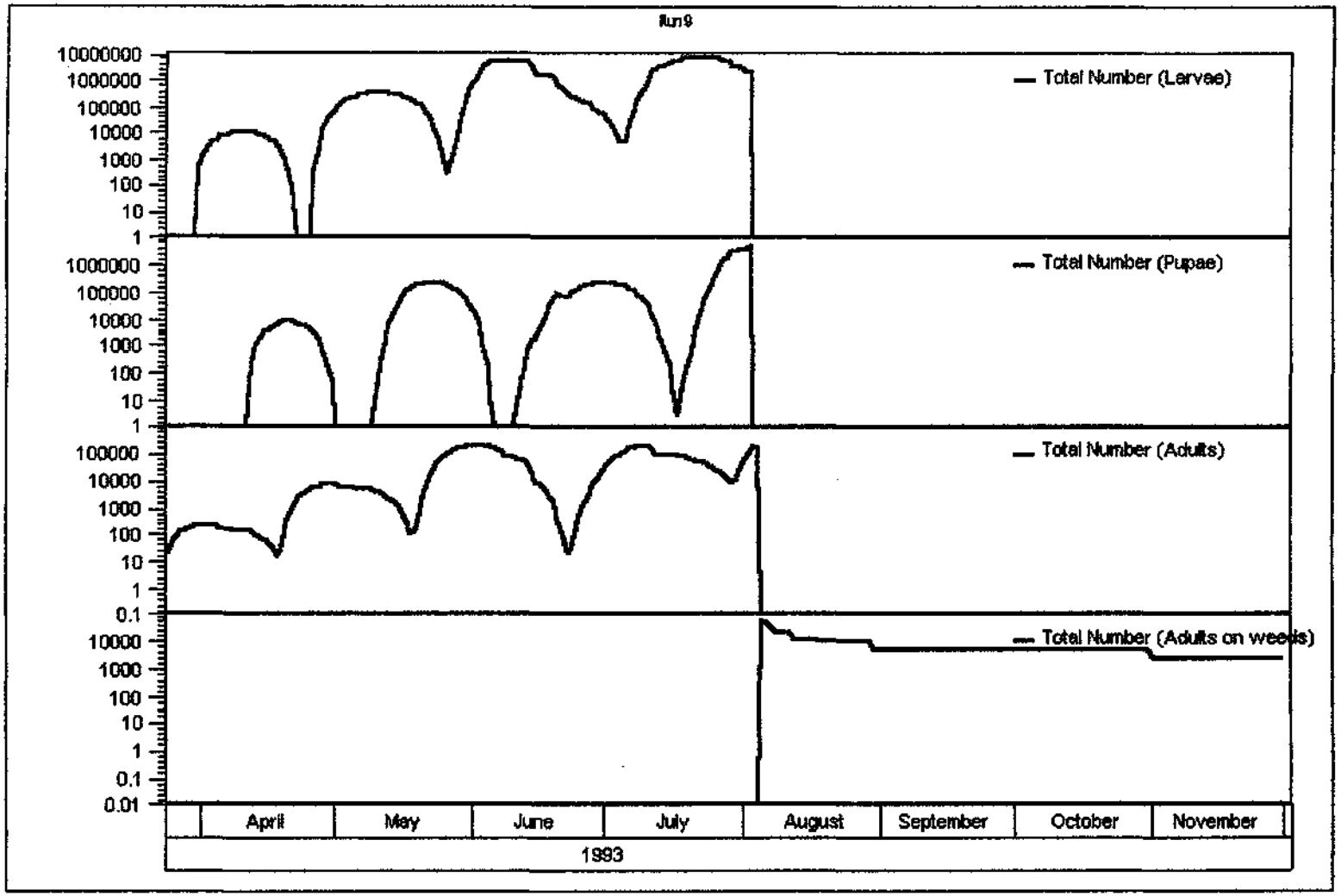

Figure 5a Simulation of a TLM population with post-harvest crop hygiene level set at 'bare ground' (i.e. level 1) in the presence of weeds. Cropping period: 24 March - 3 August.

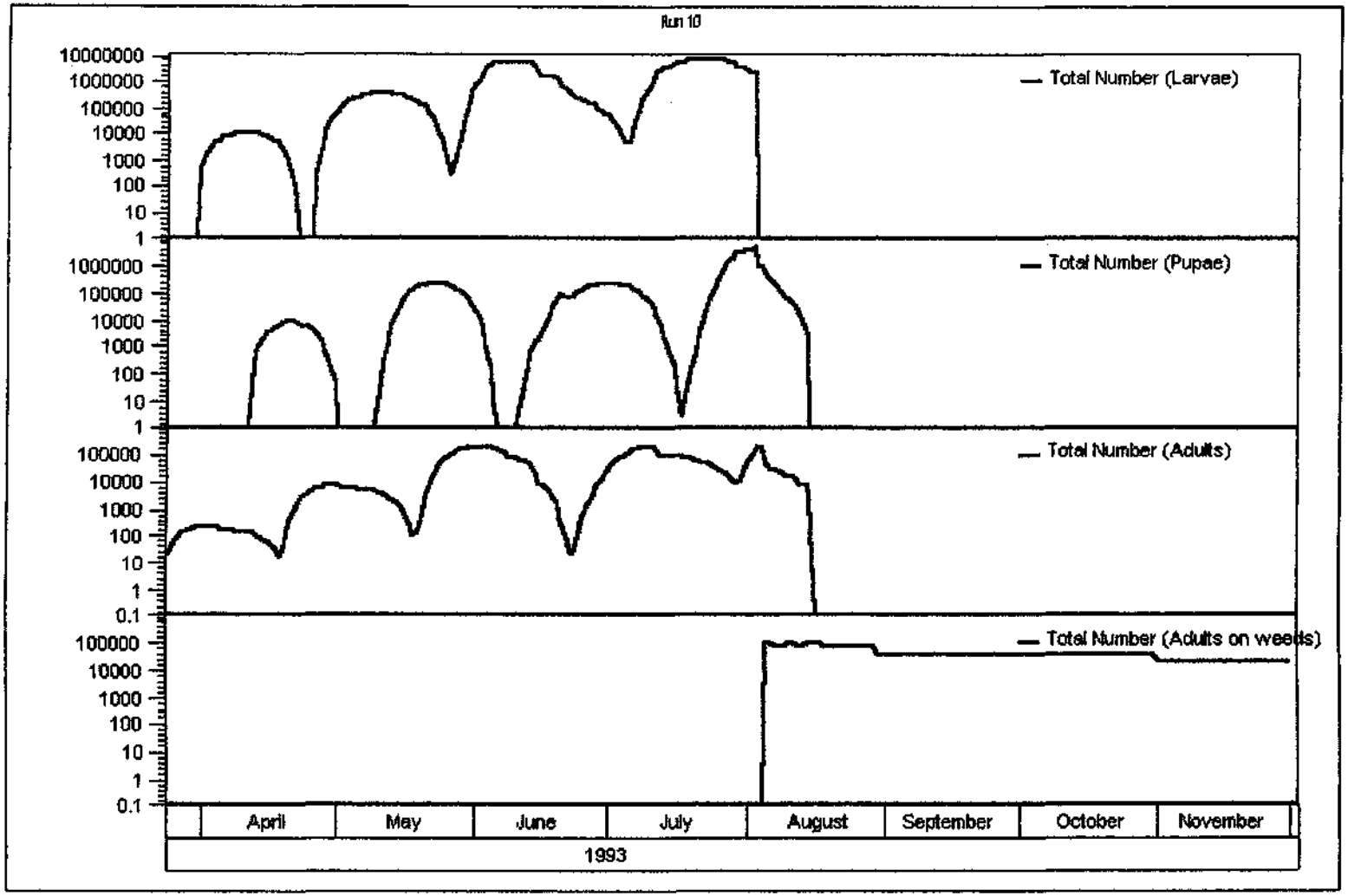

Figure 5b Simulation of a TLM population with post-harvest crop hygiene level set at 'plastic only' (i.e. level 2) in the presence of weeds. Cropping period: 24 March - 3 August.

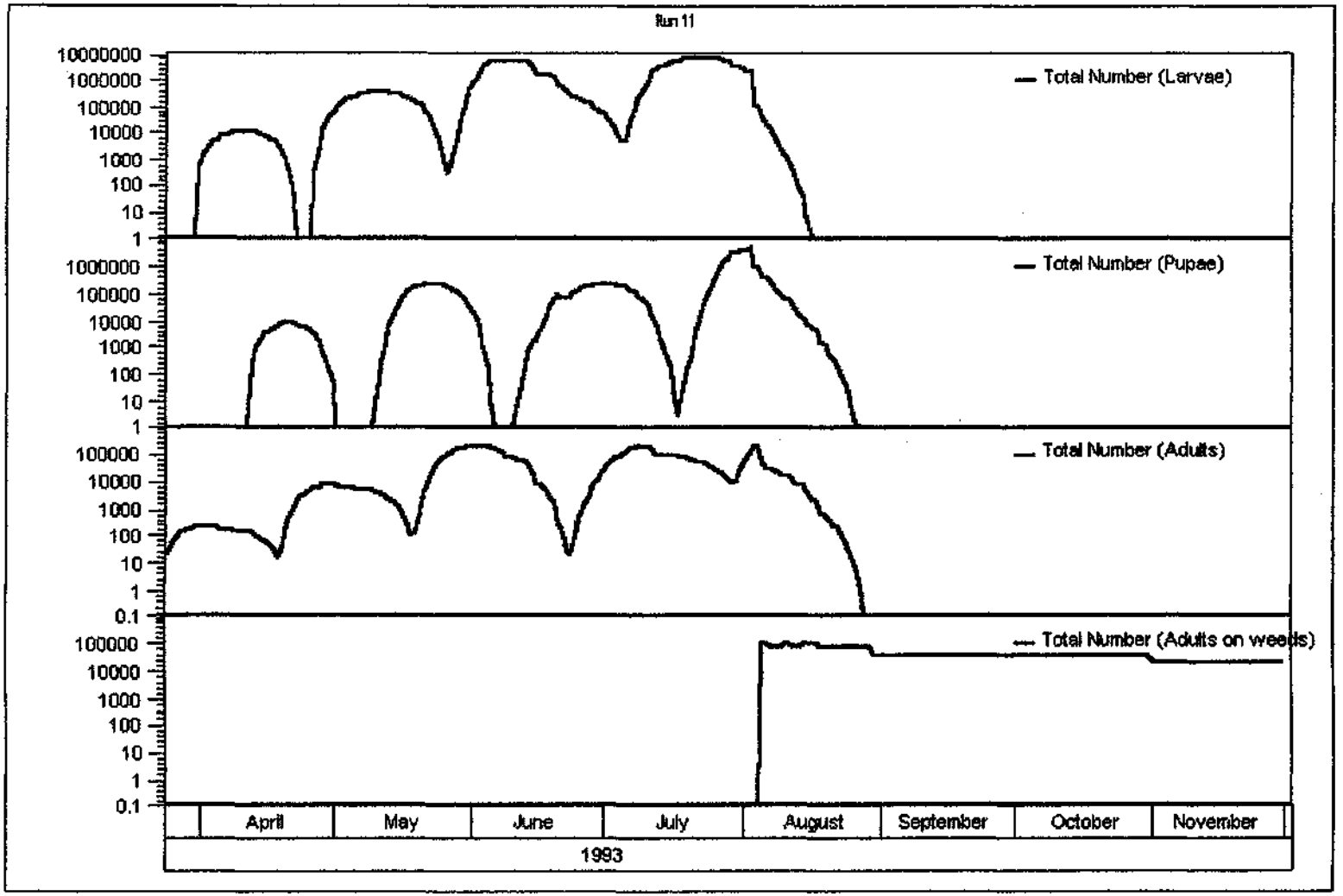

Figure 5c Simulation of a TLM population with post-harvest crop hygiene level set at 'plastic and stumps' (i.e. level 3) in the presence of weeds. Cropping period: 24 March - 3 August.

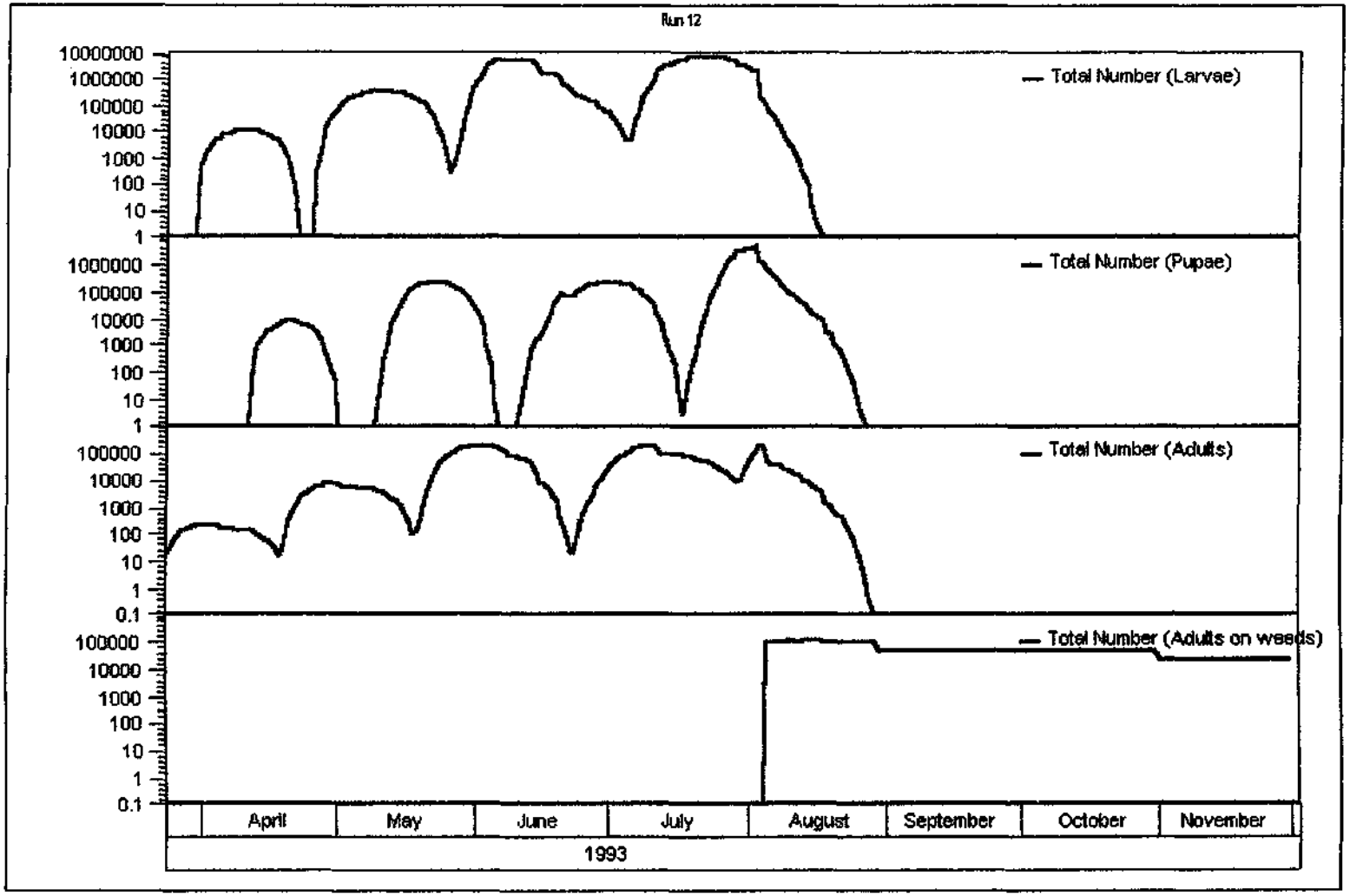

Figure 5d Simulation of a TLM population with post-harvest crop hygiene level set at 'intact plant' (i.e. level 4) in the presence of weeds. Cropping period: 24 March - 3 August.

cropping period, and the residual population persists for longer following the second harvest (Figures 6a-d).

When the second planting and harvesting events were set to occur 4 weeks after the first harvest (Table 4, runs 17-20), the number of eggs laid on the second planting was significantly lower than when replanting occurred 1 week after the first harvest (Figures 7a-d). One exception to this was where the crop hygiene level was set at 'bare ground', and in this case the number of eggs laid on the second planting was higher than when replanting occurred 1 week after harvest. This effect was likely to be due to a greater level of low temperature mortality that occurred when the replanting was earlier in the year (i.e. 1 week after first harvest) and temperatures were cooler than when replanting occurred four weeks after harvest.

The number of generations of TLM that develop on the second planting was also slightly higher (approximately 4 generations) when that planting occurred 4 weeks after the first harvest (compare Figures 6b and 7b), presumably as a result of higher daily temperature cycles. Despite this, the total number of insects to emerge from that planting was far lower (approx. 4.25×10^{7} when crop hygiene set at 'plastic only') than the number emerging from a second planting 1 week after the first harvest (approx. 1.45×10^{10}). As was the case when the second planting occurred 1 week after harvest, decreasing the level of crop hygiene increases the TLM population on the planting, and the residual population persists for longer following the second harvest.

These results indicate the benefit of increasing the length of the break between plantings, however, would this benefit still exist if weeds were present within or around the plantings? Using the settings in run 18 (Table 4) but with weeds present (Table 4, run 21), the benefit of the 4 week break in production is eliminated with a very large number of eggs laid early in the second planting ($> 10^{6}$) (Figure 8). It must also be noted that this large increase in the number of adults and therefore the number of eggs occurs even without the inclusion of any possible reproduction of adults taking refuge in the weed hosts during the production break.

The next step was to use the simulation model to help determine what constitutes an 'effective' production break in some of the regions where tomatoes are grown, particularly in those areas where tomatoes can potentially be grown all year round such as Bundaberg and Bowen.

Tomato production in Bundaberg was traditionally confined to autumn and spring until the late 1980's when there was a shift toward year round production with the main production peaks still occurring in autumn and spring (Kay and Walton, 1994). Given that TLM becomes a major pest when year round production occurs, maintenance of a production break in winter and/or summer is essential. To determine the minimal length of a production break during these periods the results from the simulations can be examined in tabular form and the number of days after harvest that adults are present can be determined. This number will represent any moths that continue to emerge after harvest (which is dependent on post-harvest treatment i.e. crop hygiene), plus the post-emergence survival of 18 chronological days of all moths in the simulation model.

Data from simulations 5-8 (Table 4) can be used to determine the minimum required length of a production break planned in winter in Bundaberg (date of last harvest 3 August). The

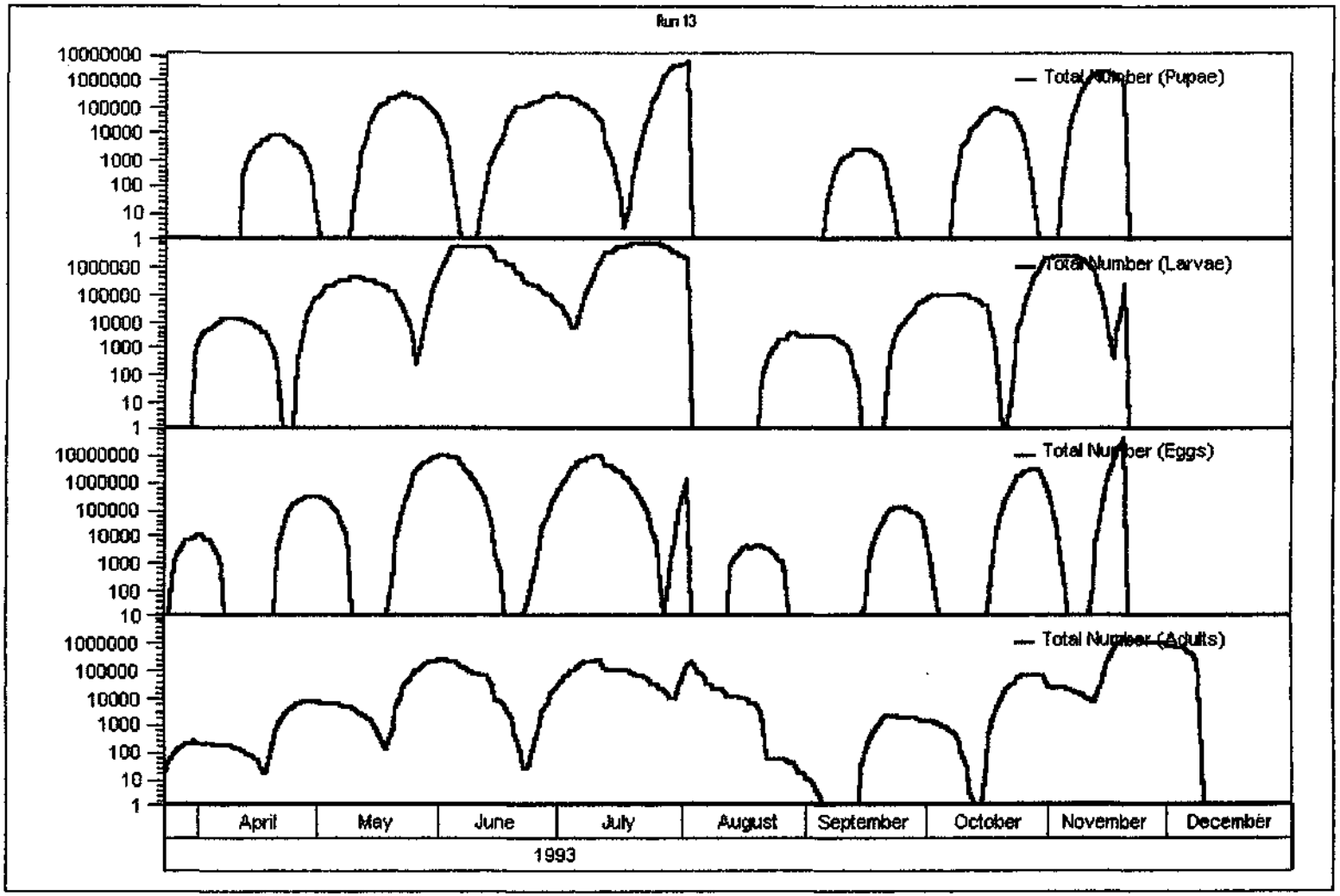

Figure 6a Simulation of a TLM population with post-harvest crop hygiene level set at 'bare ground' (i.e. level 1) in the absence of weeds. Cropping period 1: 24 March - 3 August. Cropping period 2: 10 August – 21 November.

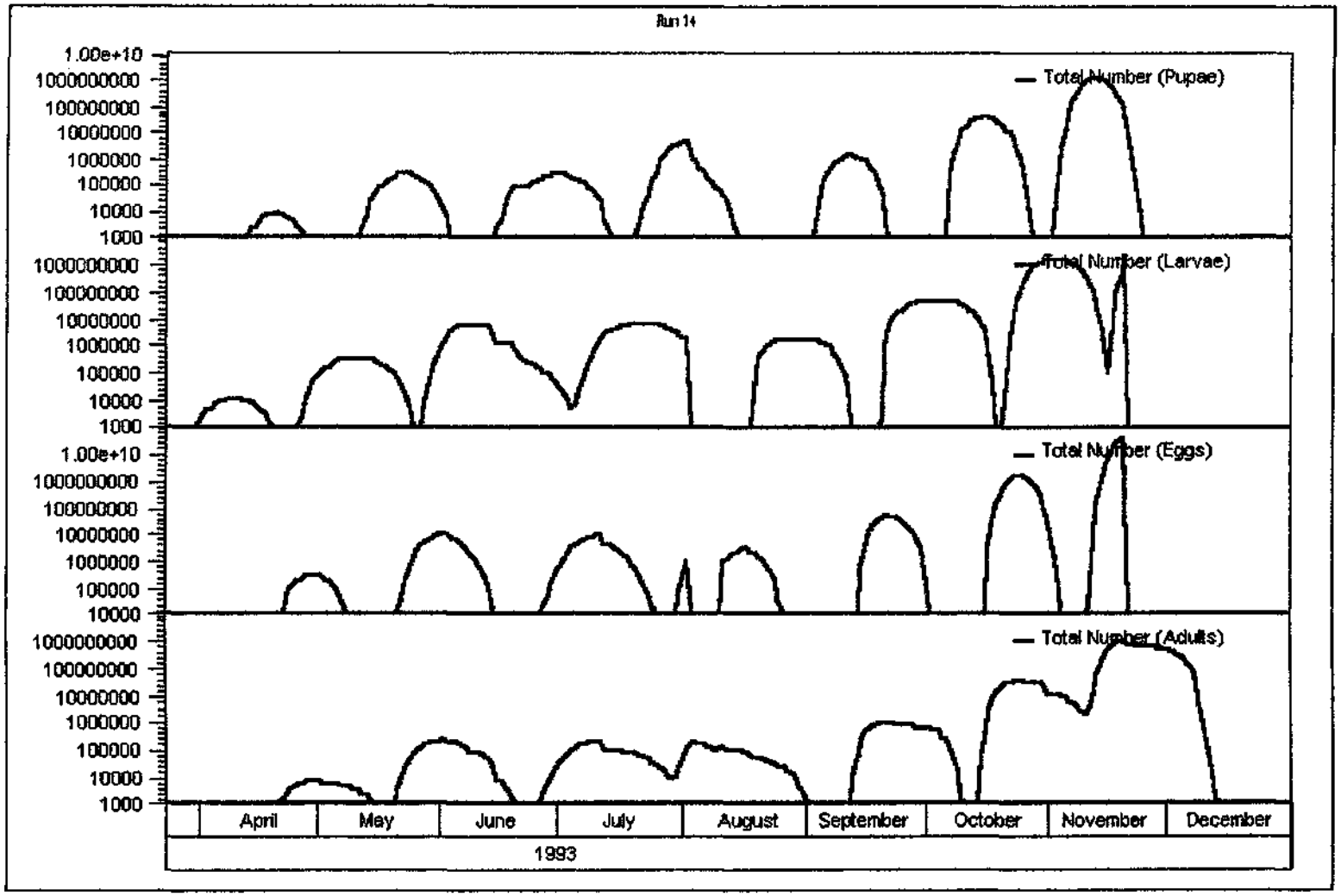

Figure 6b Simulation of a TLM population with post-harvest crop hygiene level set at 'plastic only' (i.e. level 2) in the absence of weeds. Cropping period 1: 24 March - 3 August. Cropping period 2: 10 August – 21 November.

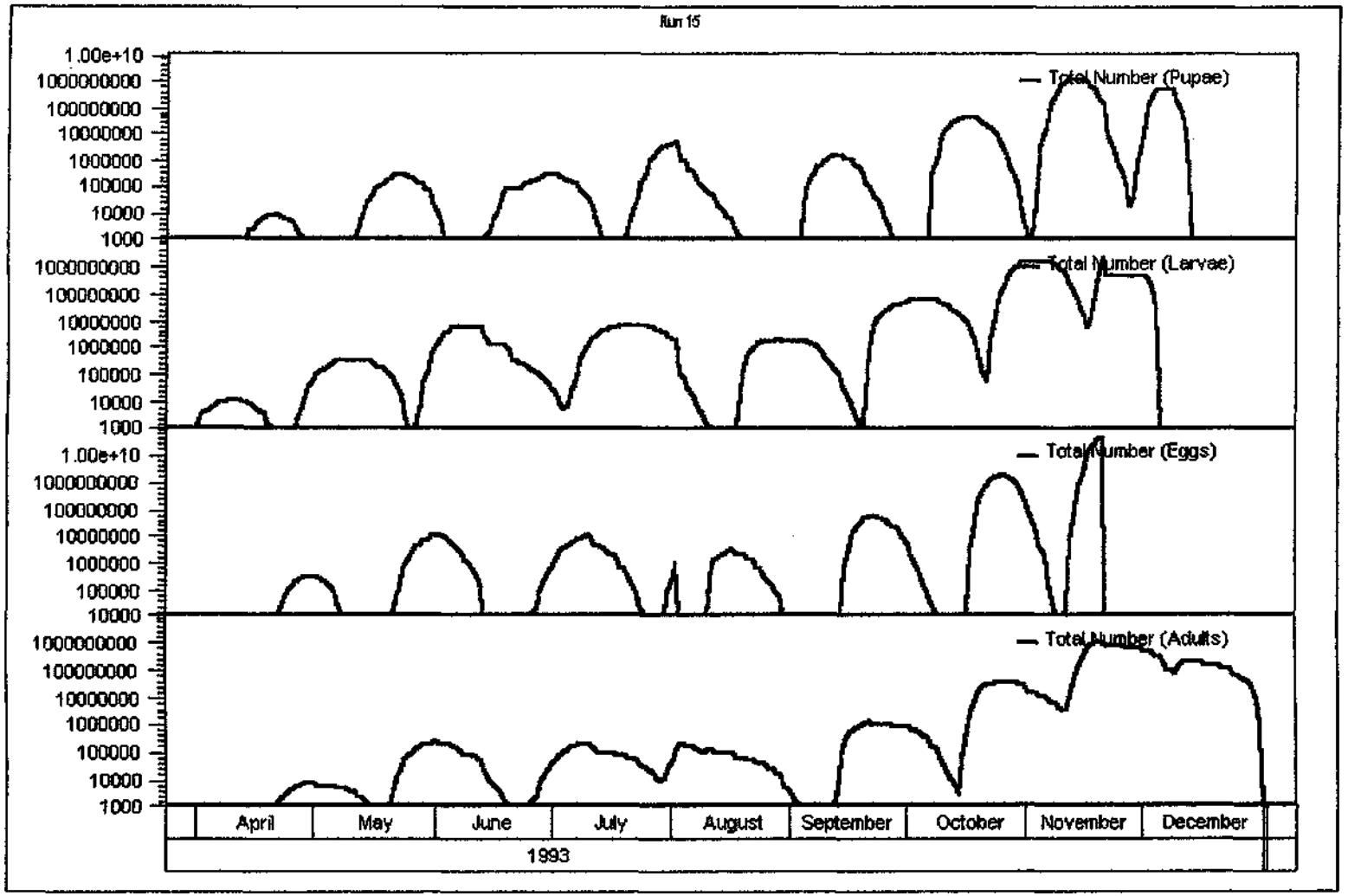

Figure 6c Simulation of a TLM population with post-harvest crop hygiene level set at 'plastic and stumps' (i.e. level 3) in the absence of weeds. Cropping period 1: 24 March - 3 August. Cropping period 2: 10 August – 21 November.

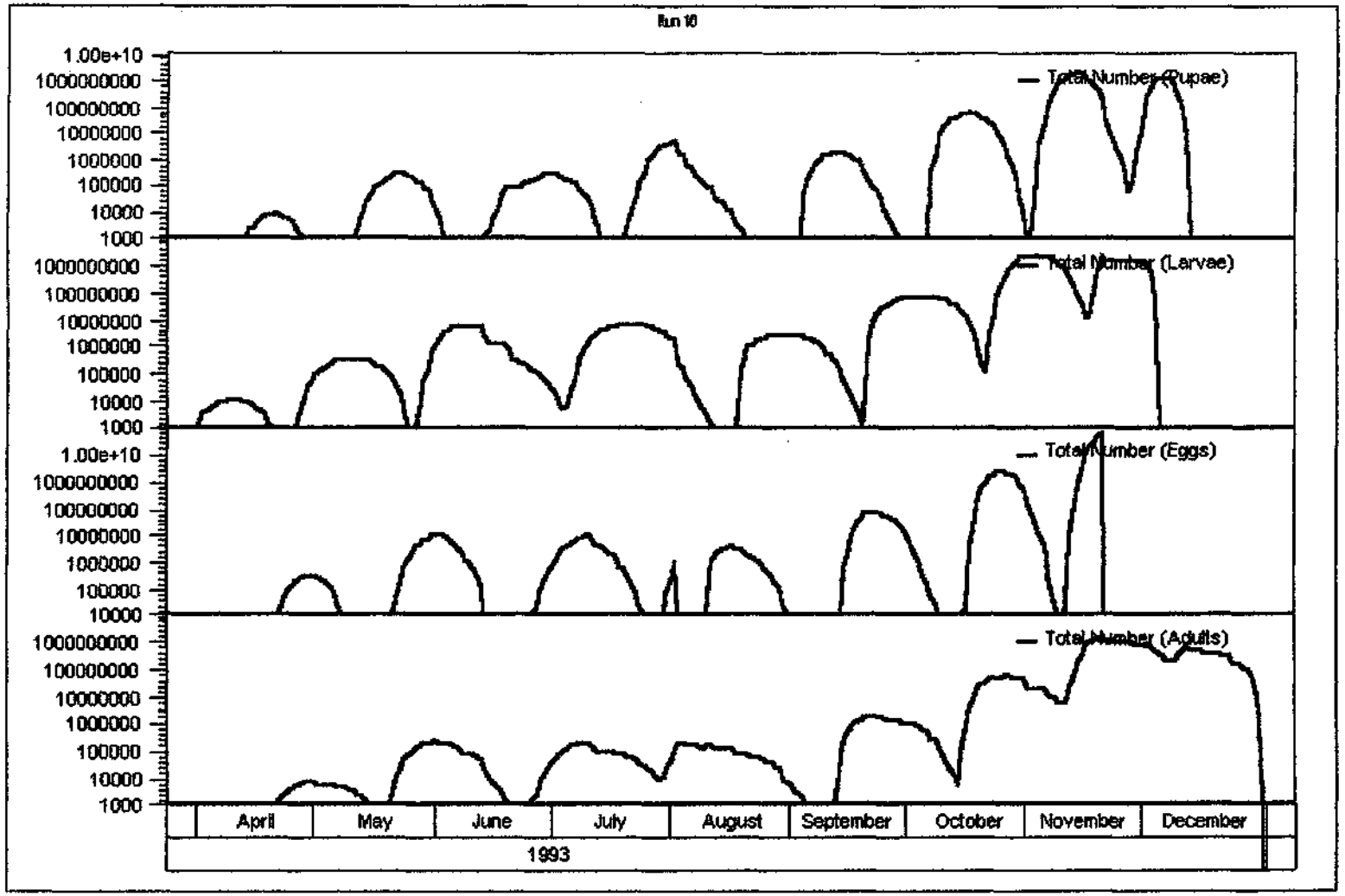

Figure 6d Simulation of a TLM population with post-harvest crop hygiene level set at 'intact plant' (i.e. level 4) in the absence of weeds. Cropping period 1: 24 March - 3 August. Cropping period 2: 10 August – 21 November.

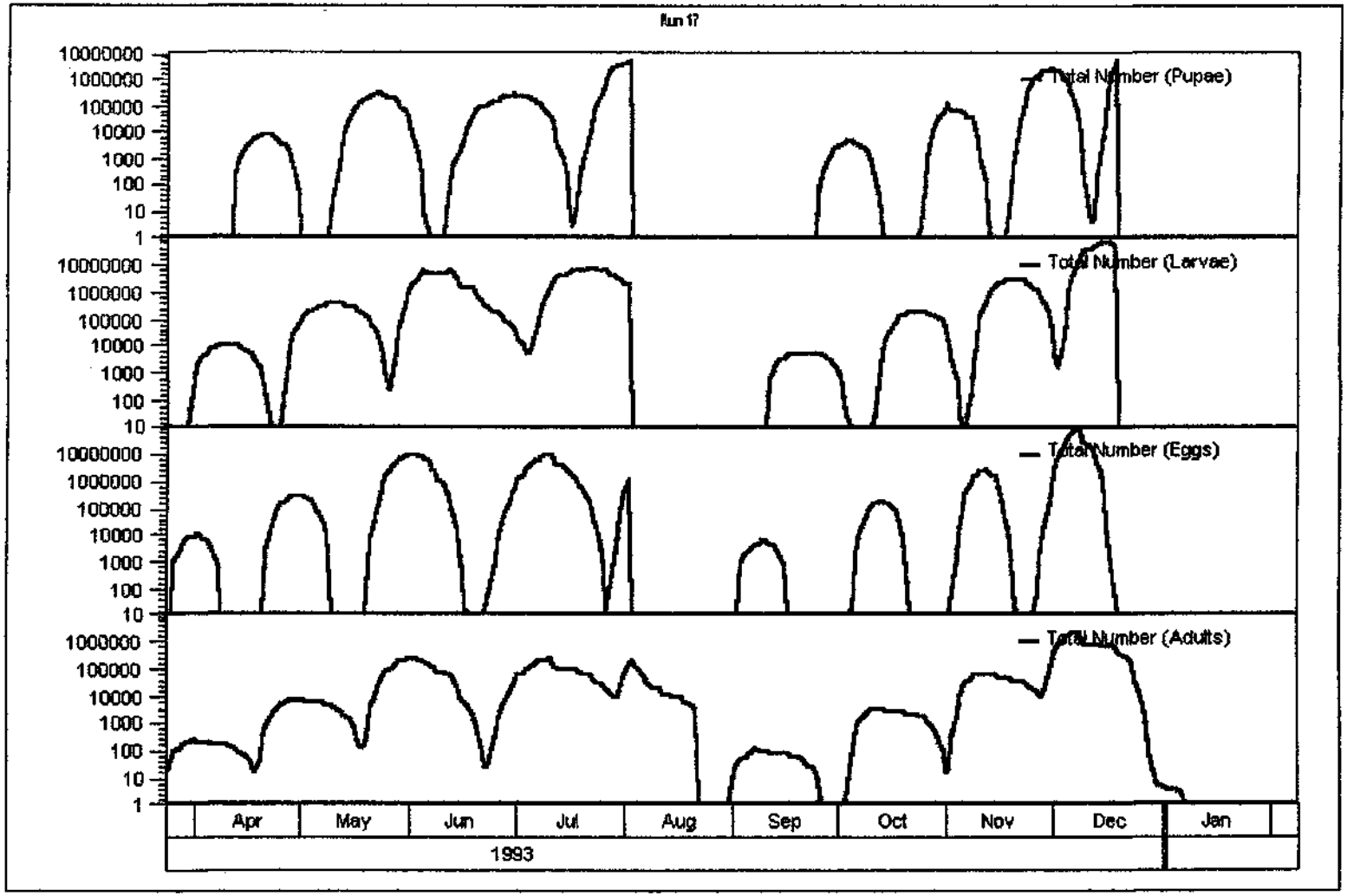

Figure 7a Simulation of a TLM population with post-harvest crop hygiene level set at 'bare ground' (i.e. level 1) in the absence of weeds. Cropping period 1: 24 March - 3 August. Cropping period 2: 31 August – 19 December.

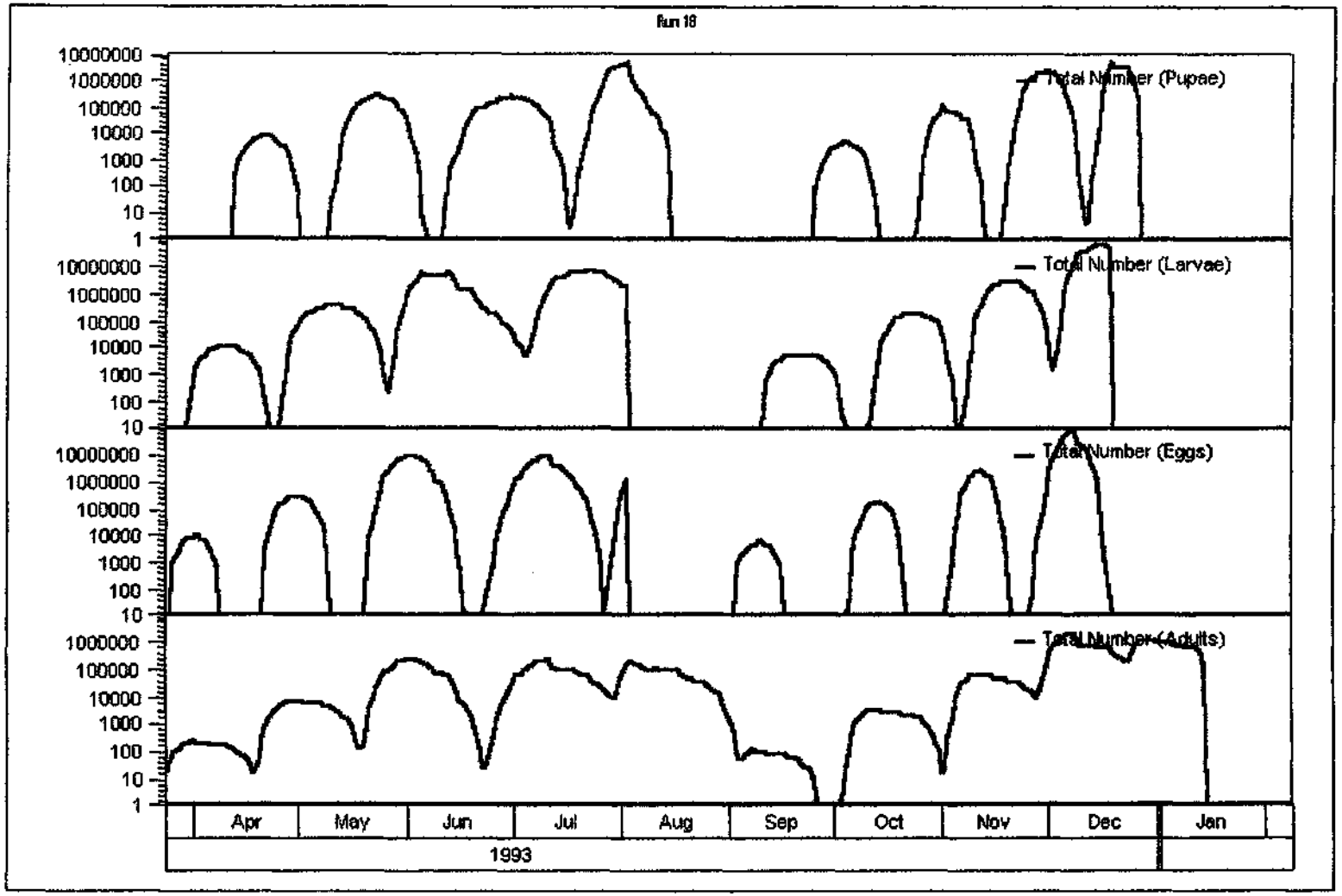

Figure 7b Simulation of a TLM population with post-harvest crop hygiene level set at 'plastic only' (i.e. level 2) in the absence of weeds. Cropping period 1: 24 March - 3 August. Cropping period 2: 31 August – 19 December.

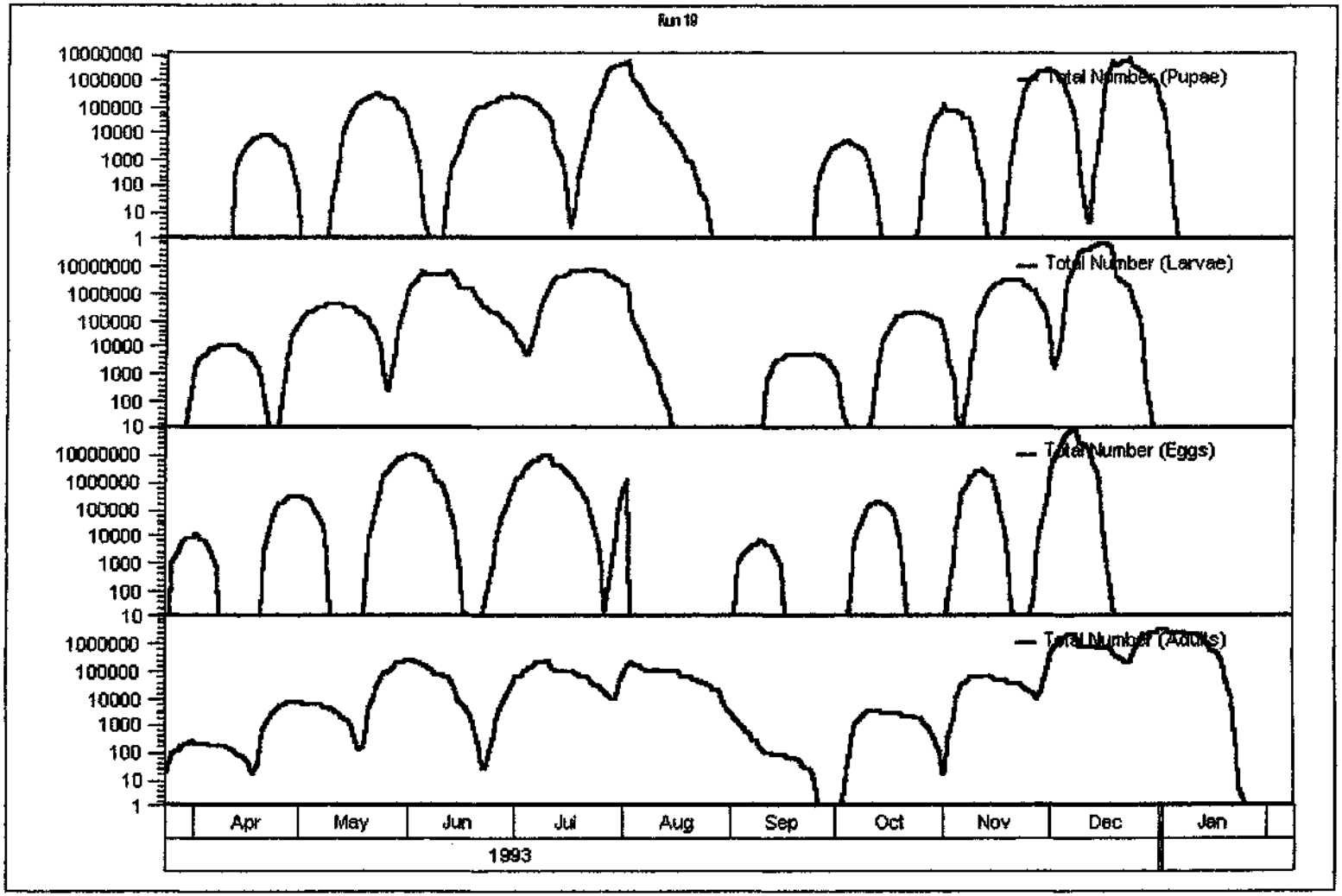

Figure 7c Simulation of a TLM population with post-harvest crop hygiene level set at 'plastic and stumps' (i.e. level 3) in the absence of weeds. Cropping period 1: 24 March - 3 August. Cropping period 2: 31 August – 19 December.

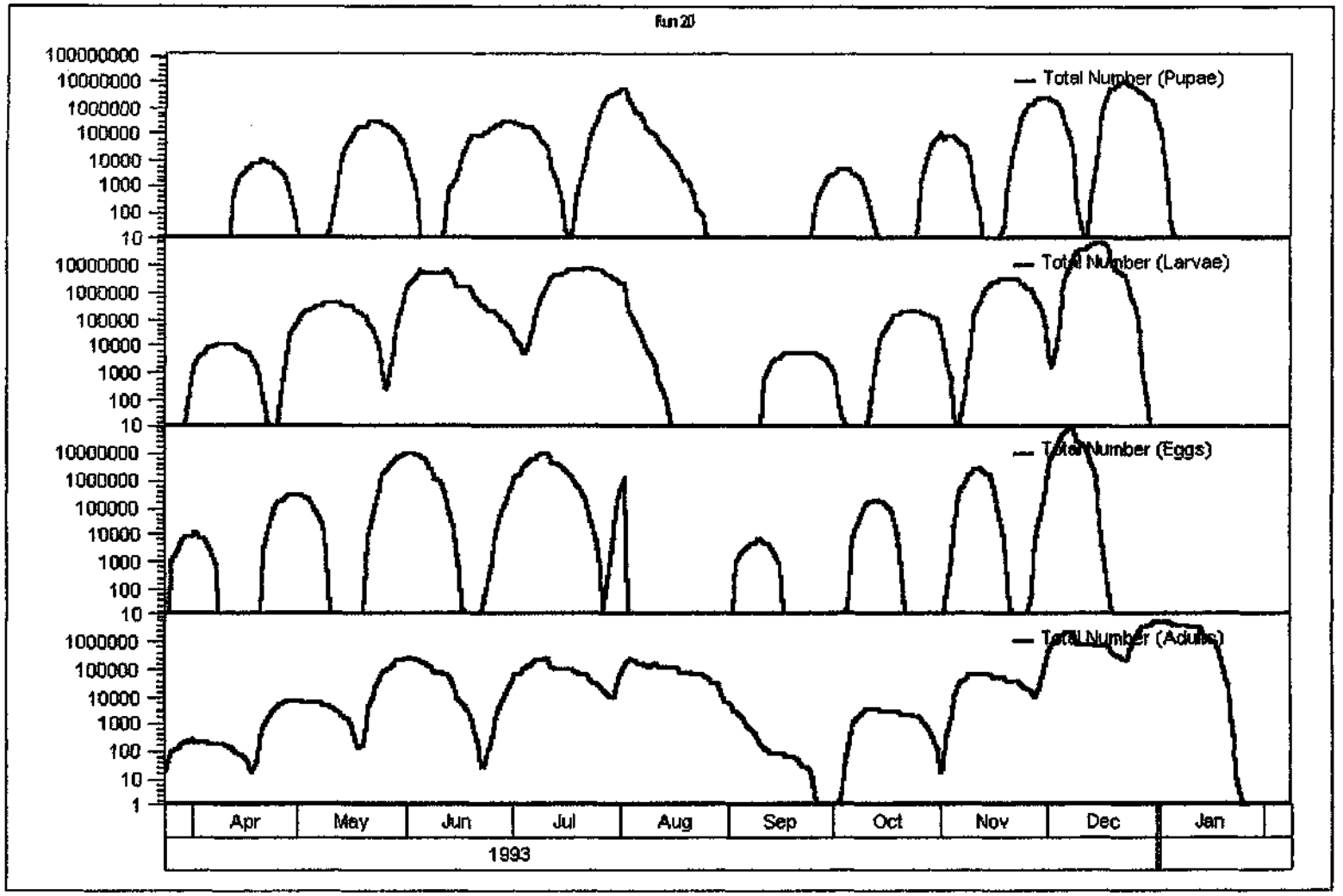

Figure 7d Simulation of a TLM population with post-harvest crop hygiene level set at 'intact plant' (i.e. level 4) in the absence of weeds. Cropping period 1: 24 March - 3 August. Cropping period 2: 31 August – 19 December.

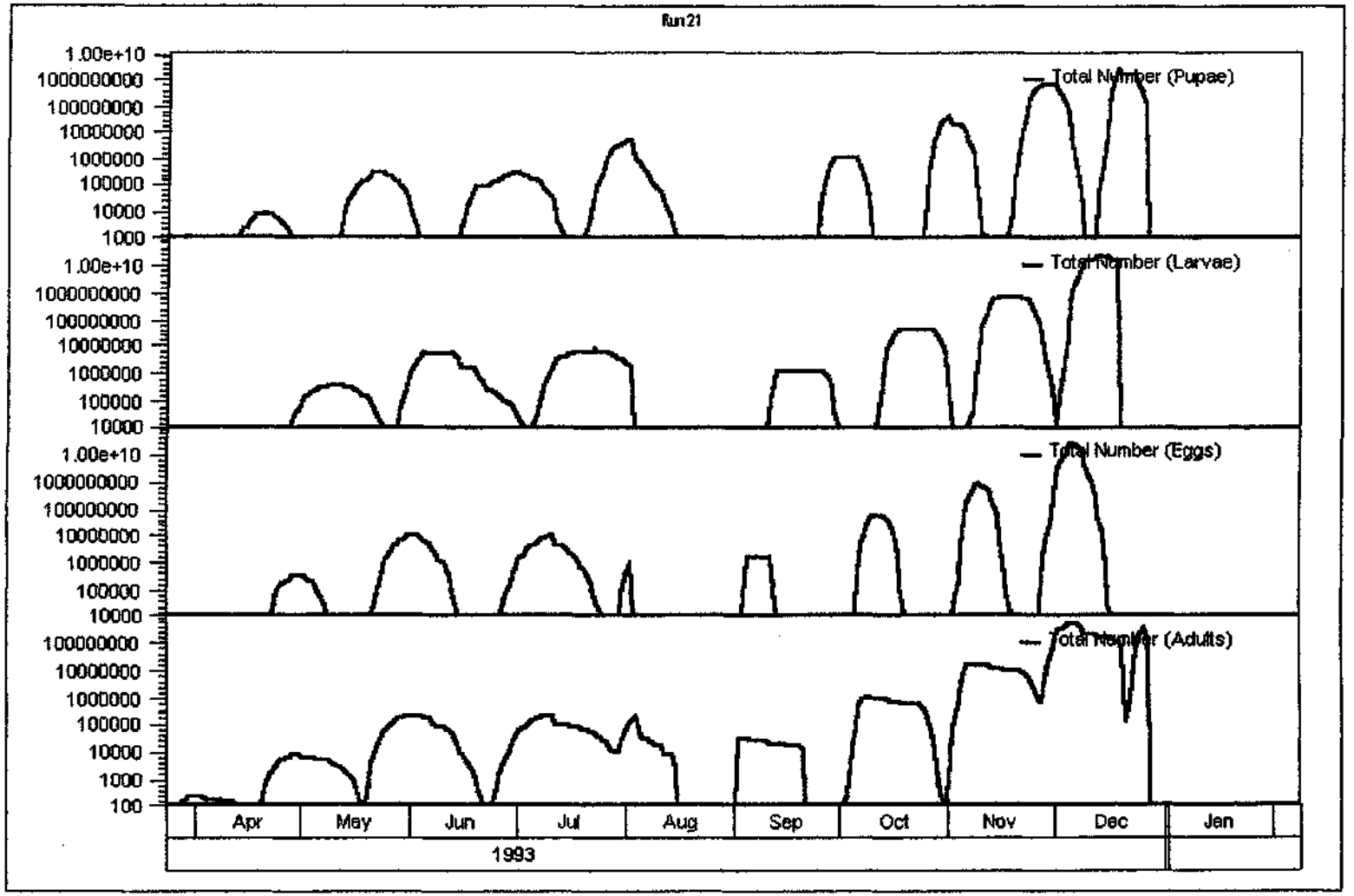

Figure 8 Simulation of a TLM population with post-harvest crop hygiene level set at 'plastic only' (i.e. level 2) in the presence of weeds. Cropping period 1: 24 March - 3 August. Cropping period 2: 31 August – 19 December.

results show that the number of days after harvest that adults are still present at each level of crop hygiene are as follows:

crop hygiene level 1 (bare ground)	18 days
crop hygiene level 2 (plastic only)	31 days
crop hygiene level 3 (plastic and stumps)	44 days
crop hygiene level 4 (intact plant)	44 days

Depending on the level of crop hygiene adopted by the grower, these numbers would therefore represent the absolute minimum length for a production break in winter in the absence of weed hosts. However, the output of the model is dependent on the level of mortality for each lifestage within each crop hygiene level. For example, at crop hygiene level 1 (bare ground), pupal mortality following harvest was initially set at 100%, that is, all pupae found among the plant litter and plastic mulch would be killed or removed after harvest. In reality, this is very unlikely as pupae may be knocked off onto the soil, or larvae may burrow into the soil underneath or around the plastic mulch to pupate. To see the effect of reducing pupal mortality at crop hygiene level 1 on the minimum required length of the production break, the settings for run 5 were again used this time with pupal mortality set at 0.95 (Table 4, run 22). The minimum length of a production break at crop hygiene level 1 increased from 18 days to 31 days, now equaling crop hygiene level 2. Any further reduction of the level of pupal mortality at crop hygiene level 1 did not alter the number of days that adults were present (i.e. the required length of the production break). Instead, only the total number of adults that emerged within those 31 days changed, with the total number increasing as pupal mortality decreased.

To determine the required length of a production break during summer in Bundaberg, the settings for run 5 were used with appropriate adjustments made to the planting and harvesting events (Table 4, run 23-26). The number of days that adults are present after harvest at each level of crop hygiene, and therefore the minimum required length for a production break at each level of crop hygiene are as follows:

crop hygiene level 1 (bare ground)	27 days
crop hygiene level 2 (plastic only)	27 days
crop hygiene level 3 (plastic and stumps)	38 days
crop hygiene level 4 (intact plant)	38 days

When compared with the minimum length of the production break required in winter, it can be seen that a shorter break is required in summer as insects that survive the post-harvest treatments develop at a faster rate at the higher temperatures experienced in late spring-early summer.

In both summer and winter the minimum length of the production break at crop hygiene level 1 is the same as that of level 2, as is the case with levels 3 and 4. The reason for this is that larval mortality was set at 100% and pupal mortality at <100% for both crop hygiene level 1 and 2, meaning that the only difference between the two treatments is in the *number* of insects that survive each treatment rather than the length of time that they are present. The exact same principle applies to crop hygiene levels 3 and 4.

In the Bowen district, the mid-1980's saw tomato production shift to year round (Kay and Walton, 1994). Following problems with outbreaks of large numbers of TLM, growers

proposed a locally enforced production break from mid-December to mid-February (Kay and Walton, 1994), however the adoption of this break by growers has been variable resulting in further outbreaks of TLM.

The settings used to determine the effective length of a production break in summer in the Bowen region are given in Table 4, runs 27 and 28. Adults were present for up to 25 days after harvest at crop hygiene level 1 (the same result would be obtained for level 2 as described above), and for up to 35 days for crop hygiene level 3 (and 4). The minimum length of a production break in summer in Bowen is therefore slightly less than that required in Bundaberg at approximately the same time of year, due to higher daily temperatures and therefore faster insect development. When the spring production season is shifted so that the production break occurs 4 weeks later in the calendar year (Table 4, run 29), the required length of the production break remains the same (i.e. 25 days at crop hygiene level 1).

In temperate climates such as the Lockyer Valley in Queensland and the Ballarat region in Victoria, cold temperatures and frosts prevent year round tomato production and winter itself acts as a reasonably effective production break. However, the effect of the various levels of crop hygiene on the post-harvest TLM population was examined using data collected from Victoria. The settings used in this simulation are given in Table 4, run 30. Due to the cooler temperatures of the region, the output from the model shows discrete generations of each lifestage throughout the cropping period (Figure 9). Development is much slower and there are large gaps between generations compared with the output from the warmer regions. The impact of the various crop hygiene strategies is therefore dependent on the timing of the harvest in relation to the presence of the lifestage. For example, larval mortality at harvest for crop hygiene level 1 is 100%, however, if no larvae are present at the time of harvest, the impact of crop hygiene is not seen. For this reason, use of the simulation model to determine the effect of crop hygiene on the post-harvest TLM population, or to determine the length of a production break (if required) in temperate climates is very limited unless the population structure at the time of harvest is known.

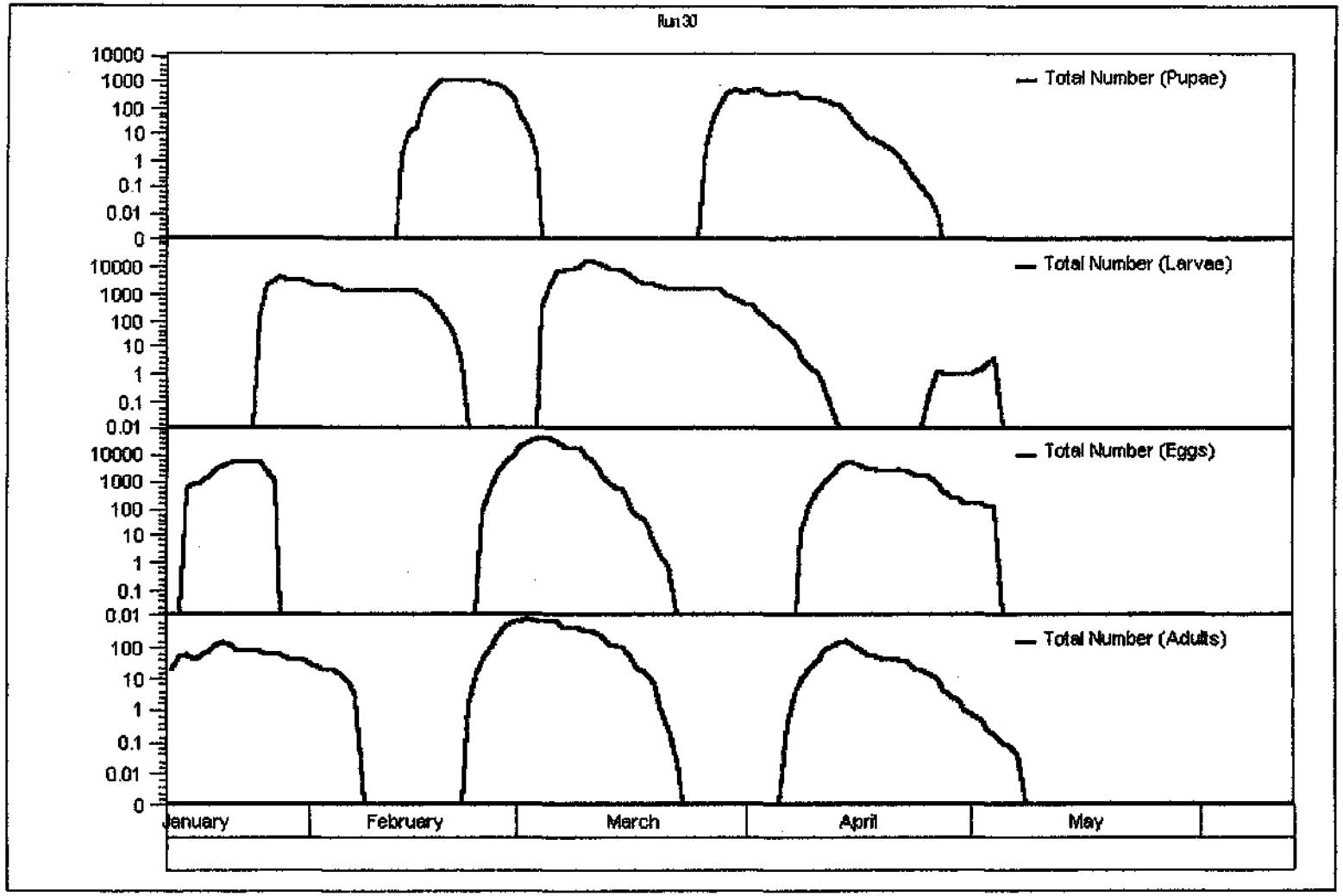

Figure 9 Simulation of a TLM population using meteorological data from Victoria with post-harvest crop hygiene level set at 'bare ground' (i.e. level 1) in the absence of weeds. Cropping period: 13 January – 5 May.

4.0 Discussion

4.1 Alternative host plant survey

In general, weeds in the Lockyer Valley district and the Bundaberg district were patchily distributed over space and time. Many growers in both districts adopted very high levels of crop hygiene, removing all weeds from the edges and within solanaceous crops during the cropping period. A large proportion of the weeds recorded over the survey period was found in newly harvested or unused blocks.

With the exception of glossy nightshade and annual ground cherry, all other weeds found during this survey have been previously recorded as hosts of TLM (Cunningham 1969; Das and Raman, 1994). However, Das and Raman (1994) define a 'host' plant as "feeding by the insect on the plant species to complete an entire generation, feeding sighted in the field, or feeding observed in the laboratory". Such a broad definition could easily lead to many plants being incorrectly included in a true host list. The act of oviposition (egg-laying) by adult insects, the presence of early instar larvae feeding on a plant, or even the presence of large larvae on a plant is not a positive indication of host plant status, since the eggs may not hatch, larvae may not complete development (they may die or move to another plant), or larvae may have moved onto a plant from an adjacent plant (Kitching and Zalucki, 1983; Zalucki *et al.*, 1994). During the survey, three weed species - green cestrum, green amaranth, and wild gooseberry - were never infested with TLM larvae despite being previously listed as hosts of TLM. Green cestrum and green amaranth in particular, were commonly recorded at sites and were frequently found within or adjacent to crops infested with TLM raising the question of whether they are hosts of TLM in Queensland. Preliminary work found that even when TLM eggs were placed onto green cestrum and green amaranth, egg hatching was reduced and larvae never established on the plants (Ford, 1998). This suggests that these two weed species are unlikely to be significant hosts of TLM in Queensland and represent a very low risk of sustaining TLM populations during a production break. Wild gooseberry was only found at a few sites in the Bundaberg district during the survey, and although it was never infested with TLM, it is difficult to comment on its host status without investigating TLM establishment and development on plants under controlled conditions. Similarly, glossy nightshade was found at a small number of sites, making it difficult to rule out as a host plant particularly as it is closely related to blackberry nightshade.

Despite being the most common solanaceous weed recorded at sites in the Lockyer Valley and Bundaberg districts, TLM infestation of blackberry nightshade was quite rare. Mines on plants that were infested were usually very small and contained only small larvae or none at all. Again, work by Ford (1998) suggested that establishment and survival of TLM larvae on blackberry nightshade was very limited (results were inconclusive). In roadside surveys and a field trial in New Zealand, Cameron *et al.* (1997) found that TLM did not infest blackberry nightshade. It may be that TLM can develop on blackberry nightshade, but it may not be a preferred host and therefore represents a low risk in terms of sustaining substantial TLM populations. Similarly, Apple of Peru may also be a low preference host for TLM, however, it was found only at relatively few sites and only one infestation recorded, making it difficult to establish its host status. Apple of Peru was not included in the TLM establishment and development research carried out by Ford (1998), and information on other host records is unfortunately lacking.

Annual ground cherry and Devil's Fig were also recorded at relatively few sites, but were quite often found to be infested with TLM larvae. The level of infestation at these sites was not high, suggesting that these weed species may be intermediate in the host range preference. This could mean that if these weeds are present in large enough numbers, they could harbour a significant TLM population.

In contrast, the thornapples, *Datura stramonium* and *Datura ferox*, were uncommon in field sites in both the Lockyer Valley and Bundaberg districts, but were often found to be infested with TLM larvae. Infested plants were found to possess multiple mines (some with more than one mine on individual leaves), and mines contained larvae varying in size from small to large. Preliminary research on establishment and development of TLM on *D. ferox* found that establishment of larvae was very high and interestingly, that larvae developed at a faster rate on *D. ferox* than on tomatoes (Ford, 1998). These data suggest that the thornapples are a highly preferred host plant for TLM and as such they are capable of sustaining large populations of TLM especially if plant density is high.

Based on the number of TLM infestations found in this survey and the level of infestation when it is recorded, preliminary guidelines for the risk of infestation with TLM for each of the weed species can be given (Table 5). These guidelines may be useful for determining the importance of control of particular weeds around and within a crop.

Table 5 Preliminary guidelines for risk of infestation with TLM for weeds found in the Lockyer Valley and Bundaberg districts.

risk of infestation	scientific name	common name
high	*Datura stramonium*	Common thornapple
	Datura ferox	*Datura*
medium	*Physalis ixiocarpa*	Annual ground cherry
	Solanum torvum	Devil's Fig
low	*Nicandra physalodes*	Apple of Peru
	Solanum nigrum	Blackberry nightshade
	Solanum americanum	Glossy nightshade (?)
very low†	*Amaranthus dubies*	Green amaranth
	Cestrum parqui	Green cestrum
	Physalis minima	Wild gooseberry (?)

† these species cannot be judged 'no risk' without further research

It should be emphasised that these are *preliminary* guidelines only, and that further research on the establishment and development of TLM should be carried out as confirmation. It should also be noted that infestation of a particular weed species by TLM could be affected by the presence of other solanaceous plants (both crops and weeds) in the vicinity, and the density, growth stage, and quality of those plants. The distance between plants may also affect the movement of TLM as adults may not be very mobile (Cameron *et al.*, 1997).

Parasitism of TLM larvae on weed species also warrants further investigation, since large numbers of parasitoids were reared from common thornapple. If parasitism of larvae on certain weed species is significant, the importance of controlling that weed around or within a crop may be reduced. Indeed, if parasitism of TLM larvae was found to be higher on a particular weed species than on tomatoes for example, these weeds could be important for attracting parasitoids into the vicinity of the commercial crop.

4.2 Temperature/development relationship for TLM larvae

Development of TLM larvae was not significantly different at different levels within the crop canopy under the imposed semi-field conditions. Further trials to test this result in the field would be useful as conditions within an actual crop may differ in terms of air movement and humidity, that in turn could affect the temperature experienced by larvae at different levels within the canopy. Should a difference in the rate of development at each level be found, the distribution of larvae on the plant would need to be considered and the model may need to be adjusted to account for variable rates of development. It is possible however, that differences in the rates of development at different levels may not be significant enough to affect the output of the model, that is, the model may not be sensitive enough that small changes in development rate significantly influence the output. Nonetheless, the data obtained under the semi-field conditions imposed in this work was useful in ensuring that the development rate of larvae in the model was within a reasonable range.

As mentioned previously, it would also be useful to examine the temperature/development relationship for eggs and pupae of TLM so that the model could be calibrated further. To examine the development of TLM eggs, adult females could be confined in small cages on the plant to enable direct laying of eggs onto the leaves and a record could be kept of the age of the eggs and their approximate location. The development of TLM pupae would be more difficult to monitor as very little is known about exactly where larvae move to pupate. Pupae can be found amongst the leaf litter at the base of the plant, under the plastic mulch (if present), and in the soil surrounding the mulch (pers. obs.), and would therefore encounter quite different environmental conditions depending on their location. Further work on the behaviour of fourth instar larvae prior to pupation, or sampling of pupae from these locations would need to be carried out in order to determine the appropriate monitoring method.

Larval 'mortality' was very high in both experiments either because larvae did not attach to the leaf or wandered off of the leaf they were placed upon. The use of laboratory reared larvae may have had a significant influence on the level of mortality found in these trials. Larvae reared under laboratory conditions would be less likely to survive fluctuating climatic conditions, and may also be preconditioned for the food source from which they were reared (although larvae used in the experiments had not been exposed to a food source before use). To overcome this it may be possible to use larvae that had been reared in a glasshouse where conditions are more likely to fluctuate to match external conditions. Alternatively, the experiment could be set up so that eggs are laid directly onto the plants, some of which could then be selected for monitoring. Simply increasing the number of larvae placed onto the plants could also ensure that enough larvae survive to be monitored although this would depend on the size of the laboratory culture that provides the larvae, and larval placement is also very time consuming.

4.3 TLM simulation model

The effect of crop hygiene on the post-harvest TLM population could be clearly seen, with high levels of crop hygiene resulting in significantly fewer adults present for a short time after harvest. As the level of crop hygiene diminishes, the number of adults present after harvest is high and the population declines at a slower rate. The presence of weeds within or around the crop was shown to reduce the benefit afforded by a high level of crop hygiene, and to amplify the effect of poor crop hygiene.

The timing of subsequent plantings relative to the initial planting was also shown to be important. Increasing the time period between plantings substantially reduced the size of the TLM population infesting the second planting. Again, the presence of weed hosts was shown to reduce the benefit gained by delaying the second planting.

In the Bundaberg district the minimum length of a production break in winter under high to very high levels of post-harvest crop hygiene was 31 days. At average to low levels of hygiene the minimum length for a production break was extended to 44 days. The minimum length of a production break in summer decreases to 27 days and 38 days for high and low levels of crop hygiene respectively. It is vital to emphasise that these estimates of the length of a production break are an absolute minimum, as they are based on simulations in which insect mortality following post-harvest treatment was set at relatively high levels. The results of Baynes (1996) indicate that some very late emergence of adults may occur even at high levels of crop hygiene suggesting that some insects will survive the treatment, and we should be conservative in setting post-harvest mortality levels in the simulation model. Further research on the effect of post-harvest crop hygiene on mortality of the various TLM lifestages would enable more realistic setting of model parameters. In addition, the presence of weeds within or around the crop may provide an alternative host for emerging adults and will extend the required length of the break depending on when and if the weeds are removed following harvest. Additional work on the role of weed hosts in sustaining TLM populations will enable more informed decisions about their effect on a production break strategy.

In the Bowen area a break in tomato production over summer would need to be a minimum of 25 days under high levels of post-harvest crop hygiene, and 35 days for low levels of crop hygiene. This prediction from the model compares favourably with field data collected in the Bowen growing region. TLM pheromone trap catches over a 2km grid in the region showed a marked decrease in the number of moths caught in the traps following the introduction of a 1 month voluntary production break in early 1994 (Figure 10). The introduction of the break followed very high levels of TLM infestation in the 1993 season as a result of some growers producing throughout the year (Abbott, 1994). An important factor to consider in this area is that tomatoes are often grown as a ground crop rather than being trellised as they are in Bundaberg (Fullelove, 1992). Because of the difference in the structure of the crop canopy, it may be possible that insects within a ground-grown crop experience quite different temperatures and relative humidity to those on a trellised crop, and that these conditions vary substantially from those recorded by standard meteorological stations. If meteorological data from these stations is to be used in the simulation model, further work should be carried out to determine the temperature profile in a ground-grown crop so that comparison with the meteorological data can be performed and adjustments made either to the data collected or to the model itself.

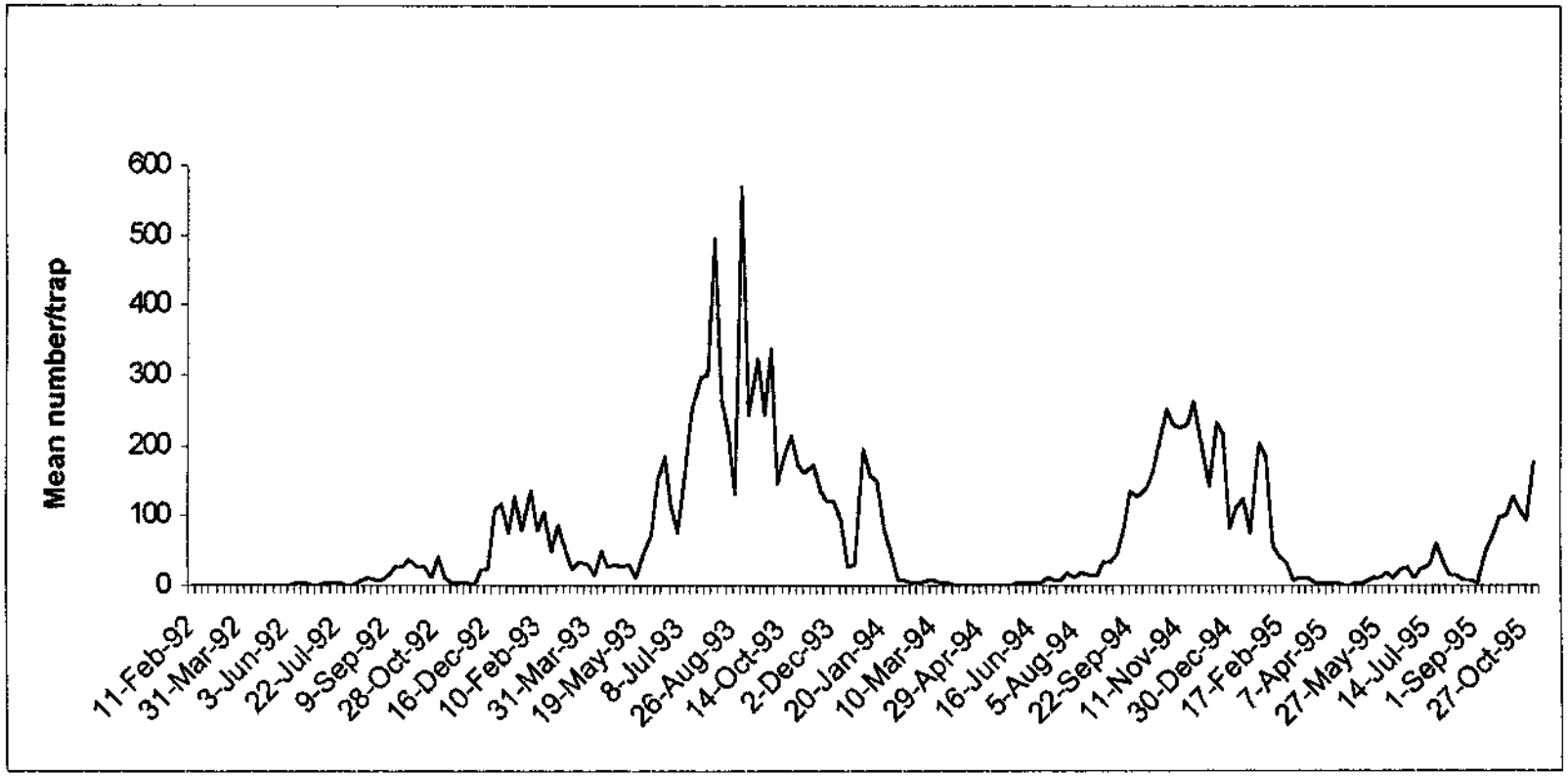

Figure 10 TLM pheromone trap catches in the Bowen growing district for the period February 1992 – October 1995. A voluntary break in tomato production was introduced by the IPM committee in Bowen in early 1994. Based on data provided by Dale and Sally Abbott (Bowen Crop Monitoring Services Pty Ltd).

The current nature of the simulation model in which discrete generations of insects exist, make it difficult to use to examine the effect of different levels of post-harvest crop hygiene on the TLM population and to determine the effective length of a break in tomato production in more temperate regions such as Victoria or the Lockyer Valley in SE Queensland. When development occurs at a slower rate, the effect of post-harvest crop hygiene in the simulations was highly dependent on the timing of harvest relative to the phenology of the TLM population. Determination of the effective length for a production break is not as vital for these areas as very low temperatures and frosts in winter prevent tomato production, thereby creating a host-free period. However, high levels of crop hygiene following the last pre-winter harvest would be important in reducing the overwintering population of TLM that can survive as pre-pupae or pupae in the soil (Lloyd, 1943). Consideration must also be given to the planting of other more cold-tolerant solanaceous crops such as potatoes in these areas. The planting of a potato crop in autumn or early winter in the vicinity of a recently harvested tomato crop will provide an alternative food source for any TLM that emerge from the tomato crop. This would reduce the benefit of a crop hygiene strategy in the tomato crop (as was the case with the presence of weeds in the vicinity), and could increase the size of the residual TLM population that survives the winter.

The presence of weed hosts within or around the tomato crop was shown to play an important role in sustaining a TLM population following harvest. However, the true extent of this role and its effect on the size of the TLM population can only be determined by further research. The work of Ford (1998) indicated that TLM adults may show a preference for oviposition on certain solanaceous weed species over others, and that there may be differences in the physiology of TLM developing on different weed species. Adult preferences for oviposition on certain weed species over crop hosts could have an important influence in determining movement of adults back onto crop hosts when replanting occurs. It also remains to be determined if development of TLM on weed hosts affects their ability to reproduce.

The relative abundance of solanaceous weeds to crop hosts may also influence their post-harvest role in sustaining a TLM population. How many weeds need to be present to sustain a TLM population that will be significant in size to cause damage upon infesting a second planting? This may depend on the weed species present if differences in the suitability of the species to act as a host to TLM are found. Differences in the 'attractiveness' of each weed species to TLM adults may mean that a particular weed has to be present in greater abundance than others in order to attract a significant number of moths. As more becomes known about the role of solanaceous weeds as hosts to TLM, the model could be varied to include the lifecycle of TLM on weeds so that the size of the population that goes on to infest a new planting will be more realistic.

In its present state, the simulation model has a number of deficiencies or limitations that may be modified as more information comes to hand. Many of the parameter values used in the model are based on estimates from data collected in laboratory-based studies. Collection of field-based data, particularly for a local area, will substantially improve the accuracy of the model. For some parameters, such as the level of mortality caused by rainfall, no data exists for TLM on tomatoes. There is limited information regarding rainfall for TLM developing on potato tubers (Foot, 1979; Rothschild, 1986) but this information may not be applicable for development within a plant canopy. Immigration of adult TLM into a new planting is currently very simply simulated with a set number of adults arriving over a period of several days. If information regarding the movement of TLM, particularly into a new planting,

becomes available, the level of immigration could be adjusted in the model so that the initial population of TLM on a new planting could be more accurately simulated.

Factors that could influence the size of the TLM population on tomato plants, such as predation and parasitism or the application of an insecticide were not included in the model. These factors could be added if the user wishes to monitor the size of the TLM population more closely rather than look at general trends in the population. Predation and parasitism could be added as an additional mortality factor within a particular lifestage, and the application of an insecticide spray could be added as an event that occurs on a particular date.

5.0 Recommendations

The survey of the Lockyer Valley and Bundaberg tomato growing districts showed that some species of solanaceous weeds, particularly the thornapples, could act as alternative host plants for TLM. To reduce the risk of infestation, and to reduce the size of the residual TLM population after harvest, solanaceous weeds should be removed from within and around a block before, during and after a tomato crop has been planted. Blocks surrounding a new planting should also be cleared as part of a weed management strategy. Some preliminary guidelines of the 'risk' of each solanaceous weed species acting as a host to TLM have been provided, however, this information needs to be confirmed through further experimentation on the oviposition preference, establishment, and development of TLM on each species. This information would also be useful in further developing the model to include the TLM lifecycle on weeds.

The role of parasitoids in regulating TLM numbers on weeds also needs to be determined, as significant numbers of parasitoids were found to emerge from TLM larvae collected from the thornapples in particular. If parasitism levels are high then the risk of that weed species acting as a significant alternative host plant for TLM, and therefore the need for its control, may be reduced.

The rate of larval development at various levels on the tomato plant was not significantly different. This finding should be confirmed within a large tomato planting where environmental conditions may vary from those experienced in this research. Should differences be found the simulation model may have to be adjusted.

Using a similar method to that used in this research for larvae, it would be useful to determine the temperature/development relationship for TLM eggs and pupae. To date this information has only been determined under laboratory conditions, and field collected data would be used to further calibrate the TLM simulation model.

Using the TLM simulation model, estimates of the minimum required length of a production break have been produced for the Bundaberg and Bowen tomato production areas. Under high to very high levels of post-harvest crop hygiene, the minimum required length of a production break in Bundaberg is 27 days in summer and 31 days in winter, and is 25 days in Bowen in summer. When average to low levels of crop hygiene are adopted, the length of the production break is increased to 38 days in summer and 44 days in winter in Bundaberg, and 35 days in Bowen in summer. It is important that these suggested production breaks are

considered conservatively particularly as the role of solanaceous weeds as alternative hosts to TLM is still largely unknown and that some of the model parameters are based on estimates.

As new information on the biology and ecology of TLM is collected, the TLM simulation model can be adjusted and/or modified to include this information. Field derived empirical data would be of particular use in improving the accuracy of the output from the model (e.g. the effect of rainfall on TLM mortality or the local movement of TLM adults). Using the model in its current form, some preliminary experiments could be carried out to validate the predictions of the model in terms of the length of the production break and the role of post-harvest crop hygiene.

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References

Abbott, D. (1994) Perspectives for the future of tomato pest management based on historical analysis. *In*: Kay, I.R. and Walton, M.P. Workshop Report: Tomato Pest Management. Cooperative Research Centre for Tropical Pest Management, Brisbane, Australia. pp 27-28.

Baynes, R. (1996) Post-harvest emergence of the potato tuber moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) from tomatoes, and an evaluation of pheromone trapping. CRC for Tropical Pest Management Vacation Scholarship Research Report, CRC for Tropical Pest Management, Brisbane, Australia. 29pp.

Briese, D.T. (1980) Characterisation of a laboratory strain of the potato moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae). *Bulletin of Entomological Research* **70**:203-212.

Briese, D.T. (1986) Geographic variability in demographic performance of the potato moth, Phthorimaea operculella (Zeller) (Lepidoptera: Gelechiidae), in Australia. *Bulletin of Entomological Research* **76**:719-726.

Broodryk, S.W. (1971) Ecological investigations on the potato tuber moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) *Phytophylactica* **3**:73-84.

Cameron, P.J., Gatland, A.M., Walker, G.P., and Wigley, P.J. (1997) Alternative host plants as refugia for diamondback moth and potato tuber moth. *In*: Proceedings of the 50th New Zealand Plant Protection Conference. New Zealand Plant Protection Society, Palmerston North, New Zealand. pp. 242-246.

Cunningham, I.C. (1969) Alternative host plants of tobacco leafminer (*Phthorimaea operculella* (Zell.)). *Queensland Journal of Agricultural and Animal Sciences* **26**:107-111.

Das, G.P. and Raman, K.V. (1994) Alternate hosts of the potato tuber moth, *Phthorimaea operculella* (Zeller). *Crop Protection* **13**:83-86.

Ford, L. (1998) Suitability of solanaceous weeds as host plants for tomato leafminer, *Phthorimaea operculella* (Zeller). CRC for Tropical Pest Management Vacation Scholarship Research Report, CRC for Tropical Pest Management, Brisbane, Australia. 19pp.

Foot, M.A. (1979) Bionomics of the potato tuber moth, *Phthorimaea operculella* (Lepidoptera: Gelechiidae), at Pukekohe. *New Zealand Journal of Zoology* **6**:623-636.

Fullelove, G. (1992) Tomato pests and disorders. Queensland Department of Primary Industries, Brisbane. Information Series QI91021.

Graf, J.E. (1917) The potato tuber moth. *United States Department of Agriculture Bulletin No. 427.*

Hargreaves, J. (1992) Pests. *In*: Fullelove, G. (Ed.) Tomato pests and disorders. Queensland Department of Primary Industries, Brisbane. Information Series QI91021. pp. 19-31.

Horne, P.A. and Horne, J.A. (1991) The effects of temperature and host density on the development and survival of *Copidosoma koehleri*. *Entomologia Experimentalis et Applicata* **59**:289-292.

Kay, I.R. (1993) Insecticidal control of *Helicoverpa* spp. and *Phthorimaea operculella* on tomatoes. *In*: Corey, S., Dall, D. and Milne, W. (Eds) Pest control and sustainable agriculture. CSIRO, Melbourne. pp. 154-157.

Kay, I.R. and Walton, M.P. (1994) Workshop Report: Tomato Pest Management. Cooperative Research Centre for Tropical Pest Management, Brisbane, Australia. 65pp.

Kitching, R.L. and Zalucki, M.P. (1983) A cautionary note on the use of oviposition records as host plant records. *Australian Entomological Magazine* **10**:64-66.

Kleinschmidt, H.L. and Johnson, R.W. (1979) Weeds of Queensland. Government Printer, Brisbane.

Lloyd, N.C. (1943) The potato moth: Experiments on its control. *Agricultural Gazette (NSW)* **54**: 323-325.

Rothschild, G.H.L. (1986) The potato moth - an adaptable pest of short-term cropping systems. *In*: Kitching, R.L. The ecology of exotic animals and plants - some Australian case histories. John Wiley and Sons, Brisbane, 143-162.

Traynier, R.M.M. (1975) Field and laboratory experiments on the site of oviposition by the potato moth, *Phthorimaea operculella* (Zell.) (Lepidoptera: Gelechiidae). *Bulletin of Entomological Research* **65**: 391-398.

Trivedi, T.P. and Rajagopal, D. (1992) Distribution, biology, ecology and management of potato tuber moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae): a review. *Tropical Pest Management* **38**: 279-285.

Wilson, B.J., Hawton, D. and Duff, A.A. (1995) Crop Weeds of Northern Australia. Department of Primary Industries, Brisbane.

Zalucki, M.P., Murray, D.A.H., Gregg, P.C., Fitt, G.P., Twine, P.H. and Jones, C. (1994) Ecology of *Helicoverpa armigera* (Hübner) and *H. punctigera* (Wallengren) in the inland of Australia: larval sampling and host plant relationships during winter and spring. *Australian Journal of Zoology* **42**:329-346.

Appendix 1 – Final Report for Vacation Scholarship

Post-harvest emergence of the potato tuber moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) from tomatoes, and an evaluation of pheromone trapping

Renee Baynes

February 1996

Post-harvest emergence of the potato tuber moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) from tomatoes, and an evaluation of pheromone trapping.

Renee Baynes

Presented at the CRC for Tropical Pest Management,
The University of Queensland

19 February, 1996

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Abstract

This project looked at pheromone trapping of the potato tuber moth, *Phthorimaea operculella* (Zeller), and at the emergence of moths from an old crop under various post harvest treatments. In pheromone trapping studies, two trials showed no significant differences in numbers of moths caught when the trap water reservoirs were full, 3/4, 1/2 or 1/4 full. A series of trials were undertaken to evaluate the attractiveness of lures aged 2, 4, 6, 7 and 8 weeks. No significant differences were found between catches using lures of these ages and catches using new lures. The performance of a new experimental lure supplied by Agrisense was evaluated against the performance of the standard Agrisense lure. No moths were caught with the experimental lure. Emergence trapping studies looked at the length of time moths emerged from the old crop on which different post-harvest treatments had been imposed and how many moths emerged from each treatment. (Treatments were : bare ground, plastic mulch only, plastic mulch and stumps of plants remaining and all plant and plastic material remaining.) Moth emergence leveled off after 24 days but another phase of emergence was experienced at 34 days. Significantly fewer($P<0.05$) moths emerged by 24 and 34 days from the bare ground treatment than from the plastic mulch and stumps treatment and form the treatment where all plant material and plastic mulch remained.

Introduction

The potato tuber moth, *Phthorimaea operculella* (Zeller), also known as the tomato leafminer (see plate 1), has been a serious crop pest in the Bundaberg region for several years and is now regarded as the major pest of tomatoes (Kay, 1993a). Tomato crops grown in the Bowen region previously did not suffer as severe leafminer damage but now leafminer has become an important pest in this region also. (I. Kay, pers. comm., 1995). The pest is present but not severe in the Lockyer Valley region (P. Deuter, pers. comm., 1996)

Leafminer may damage a tomato crop in a number of different ways. In seedlings the larvae may bore into stems damaging the conductive tissue of the plant. Older plants may suffer tunnel mines in the leaves (which is of minor importance) (see plate 2) and damage to the fruit (see plates 3 and 4). Larvae may either tunnel into the sides of fruit making it unmarketable or tunnel under the calyx. When smaller larvae enter under the calyx, damage may not be immediately apparent. If this type of damage goes unnoticed at the farm level, damaged to the fruit may become apparent once the it reaches retail shops. Entry points of larvae into fruit also provide access for pathogens such as rots, leading to further breakdown. Through these types of damage it is possible that growers may lose as much as 50-60% of their yield. Leafminer is also a quarantine pest. New Zealand has a nil tolerance level for leafminer in tomatoes imported into that country.

Queensland produced 76.22% of Australia's fresh market tomatoes in 1992-93. Of this, the Bowen and Bundaberg regions are most important, producing 45% and 40% of the state's output respectively. The South East region (Lockyer Valley and Redland Bay) produces 13% of the state's total (Maltby, 1995). With possible damage figures being so high, the economic implications at the grower and regional levels may be severe if the pest is not adequately controlled.

The leafminer is a member of the Gelechiidae family. The larval stage (see plate 5) feeds on Solanaceous hosts such as tomato, potato, tobacco and eggfruit. After hatching from eggs, larvae tunnel into leaves or fruit and feed on the mesophyll tissue (Rothschild, 1986). Larvae usually leave the leaf or fruit to pupate just beneath the soil surface, but may roll a leaf to form a pupal chamber (Horne, 1994). Adults rest in concealed sites under leaves, clods of soil and other debris during the day. After sunset, females lay their eggs, either singly or in small groups. Eggs are laid on the soil near the base of a host plant or on the undersides of its leaves (Rothschild, 1986). Haines (1977), Rothschild (1986) and Trivedi and Rajagopal (1992) have reviewed leafminer distribution, biology and ecology.

Several factors seem to contribute to the severity of leafminer damage in the Bundaberg region. Most significantly, tomatoes, or some form of other cultivated host, are grown all year round. This, combined with the warm temperatures of the area, allows the pest to breed and develop throughout the year. In contrast, the Bowen region has a production break in the summer. This possibly allows for a break in the lifecycle of the pest, thereby reducing its numbers. Also, insecticides are used heavily in the Bundaberg area for the control of heliothis. This reduces the numbers of beneficial insects present to control leafminer. Contact insecticides are not efficient in the control of leafminer, as larvae are protected by their habitat. Also, resistance to insecticides used may be present as some insecticides (eg. methamidophos and sulprofos) which were effective previously, (Hargreaves and Cooper, 1979) are no longer effective (Kay, 1993a). Crop hygiene is recommended by consultants in the Bundaberg region (J. Hall pers. comm., 1995). Removing a crop from the field as soon as possible after harvest finishes also removes the leafminer's habitat. This means the pest is limited in its ability to persist in the field and reinfest future crops.

Increasing pest problems and reduced profitability of tomato production lead to a tomato pest management workshop being held at the Cooperative Research Centre for Tropical Pest Management, Brisbane in April 1994 (Kay and Walton, 1994). This workshop, involving industry, grower and research representatives, identified a number of key issues as being important for improved tomato production in Australia. Among these, a lack of knowledge of pest and beneficial insect ecology was identified. A number of questions about leafminer were raised, including: the length and timing of production break required for effective management; how pheromone trap catches relate to field populations; and how long the pest can survive without a host present. To further understand leafminer ecology, it was decided that the number of generations per crop should be identified, and that the distribution of natural enemies and interactions between

beneficial insects be determined. Also, the use of the beneficial aspects of the natural production break in Bowen as a model for artificial breaks elsewhere was identified as a possible control measure.

This project was designed to help address two of the objectives put forward at the tomato pest management workshop, namely the production break strategy and the monitoring of leafminer moth populations.

To be effective a production break must be long enough to interrupt the lifecycle of the pest. There is anecdotal evidence that leafminer moths are able to emerge from old cropping ground for many weeks after the destruction of the crop. If this is so, the production break would need to be long enough for these moths to emerge and die without finding a suitable host on which to oviposit. The length of the emergence period may be affected by various post-harvest treatments. A trial was designed and undertaken to see for how long moths emerged from an old crop under different post-harvest treatments.

The use of pheromone traps to determine field populations was also addressed. Some insects, including the tomato leafminer, communicate with the aid of behaviour modifying chemicals known as pheromones. These chemicals often induce directional attraction towards the source of the pheromone (Carde and Elkinton, 1984). In the case of the leafminer, pheromone is produced by the female moths to attract males. This form of communication may be manipulated to provide information or control measures within a crop. Pheromones may be used to survey, or detect, the pest within a crop (Carde and Elkinton, 1984). Also, pest population levels may be estimated, which allows the grower to compare the population to a predetermined economic threshold population level and implement control measures if necessary.

Mass trapping may also be effected using pheromones. If a high enough density of traps is deployed it may be possible to eliminate a large proportion of the population thereby reducing crop damage (Carde and Elkinton, 1984). Pheromones may also be used to disrupt mating patterns. High concentrations of pheromone are released in the field to confuse the male moths so they are unable to find the females. Alternatively, pheromones may be applied at high rates to side plots to lure males out of the crop (Carde and Elkinton, 1984).

For leafminer, pheromone traps are used widely as a monitoring tool (Raman 1988). The pheromone (comprising of trans-4, cis-7, tridecaelienl-ol acetate and trans-4, cis-7, cis-10-tridextrien-1-ol acetate) (Raman 1988), is expensive to produce and therefore is not used for mating disruption. A number of factors may affect trap catches of leafminer, including trap design, trap height (vertical height within a crop), trap location within a field, pheromone dose and lure age. Kay (1993b) evaluated a number of different trap designs and also investigated trap height, both in regard to catch efficiency. He found that a horizontal water trap made from a length of PVC stormwater pipe was most efficient. However, this design had some disadvantages. Most importantly the water

reservoir is shallow and subject to rapid evaporation under hot conditions. This means the trap needs to be cleared quite regularly, possibly every 3 days. Vertical water traps (see plate 6) (described in the Materials and Methods section), while not having the catch efficiency of horizontal traps, are used widely in the Bundaberg region. These overcome the evaporation problem associated with the horizontal traps as they have a deep water reservoir. Vertical traps may be cleared as little a once a week. Kay (1993b) found that traps positioned in the upper part of the crop canopy caught more moths than traps lower down in the crop. Traps are usually nailed to the top of trellis posts within a tomato block.

A number of questions about pheromone trapping for leafminer are still evident. This project aimed to investigate two of these questions. Firstly, does the depth of the water reservoir in the vertical traps affect the number of moths caught in the trap? Water levels from full to a quarter full were compared. Secondly, how long do Agrisense lures remain attractive to male moths? Trap catches using lures aged from 2 to 8 weeks were compared to catches using fresh lures.

Agrisense have developed an experimental lure that does not contain the pheromone normally used but instead uses an analogue. This analogue is far cheaper and easier to produce than the pheromone and a trial undertaken by Agrisense in Egypt had indicated that the analogue was as effective as the pheromone (E. Casagrande, pers. comm., 1996). The project also tested the experimental lures containing the analogue against standard lures containing pheromone and compared their effectiveness in attracting male moths.

MATERIALS AND METHODS

1. Pheromone trapping studies

Evaluation of Different Reservoir Waterlevels in Vertical Pheromone Traps

Two trials were carried out at different times and at different locations. Both trials were set out in randomised block designs with four treatments and five replicates (see Appendix 1 for layouts). The trap design used was a T-shaped vertical trap (See Plate 6). This trap consists of two parts. The top section is a 150 mm length of 50 x 100 mm PVC downpipe, with a circular hole cut in the centre of the bottom side. The vertical reservoir is a 220 mm length of 90 mm PVC stormwater pipe with the bottom end covered with an end cap. The top fits into the hole in the top section and is held in place with a wire pin. The reservoir is filled with water and detergent and the lure is suspended above it. The treatments imposed were full, 3/4, 1/2 and 1/4 full (this corresponds to 5, 11, 17 and 21 cm below the pheromone lure). The Agrisense lures used were all from the same batch (No. PO 055A).

The traps for the first trial were attached to the top of the trellis posts (at the side) 10 rows (approximately 18m) apart and approximately 20m apart within rows in a commercial block of tomatoes off Goodwood road, Bundaberg. Traps were placed these distances apart to minimise interactions between the traps. Traps were left out for three nights then the total number of moths caught in that period were collected, stored in alcohol and taken back to the laboratory for counting. The traps were put out on the 27/12/95 to the 30/12/95.

The second trial took place in a commercial eggfruit block on Dr. Mays Crossing road, Bundaberg. Traps were placed as far apart as possible to minimise interactions on stakes erected in the middle of the eggfruit block (See plate 7). Traps were put out on the 31/1/96 and cleared on the 2/2/96.

ANOVA were performed on the data from both trials using the QDPI RANB Computer statistical package. Data were transformed using log (x+1) before analysis.

Aging of Standard Lures Used for Pheromone Trapping.

Agrisense lures were tested to determine the effect of aging on their attractiveness. The experiment used a completely randomised design. Two treatments and five replicates were used for the first 2 trials, 4 replicates were used for the last 3 trials The treatments were the aged lures and fresh lures. The lures were assessed at 2, 4, 6, 7, and 8 weeks old. Lures were removed from traps after each run of the experiment and aged by placing them in the top of a trap at the QDPI Bundaberg Research Station and exposing them to approximately the same conditions as would be experienced in the field.

The traps used were the same as described in the previous section. The first 2 trials for 2 and 4 week were carried out at the same Goodwood road site mentioned in the previous section. The trial for 6 week old lures was carried out in a commercial block of tomatoes on Farnsfield road, Bundaberg. The 7 and 8 week old trial were carried out in the eggfruit block mentioned in the previous section. Traps were left out for four successive nights for the trials at 2, 4 and 7 weeks and three successive night for the 6 and 8 week trials. The total number of moths caught in a trial were collected, stored in alcohol and taken back to the laboratory for counting. The first trial took place from the 15/12/95 to 19/12/95 and the last from the 9/2/96 to the 12/2/96 .

A t-test was carried out in each set of data collected from the trials using the Stastistix computer statistical package.

Evaluation of an Experimental Agrisense Lure

The experiment had a completely randomised design with two treatments and five replicates. Traps baited with either the experimental analogue lure or a standard Agrisense lure were nailed to the top of trellis posts 20m apart along rows and 18m apart across the rows. Traps were left out for four successive nights and the total number of moths caught were collected, stored in alcohol and taken back to the laboratory for counting. The trial took place from the 15/12/95 to 19/12/95.

2. Emergence Trapping

The trial was carried out at the QDPI Bundaberg Research Station in a block of tomatoes previously used for entomological experiments. This block was of the variety Flora Dade and received no insecticides during growth, but fungicides had been applied. Other cultural practices (such as irrigation) were carried out as normal. The crop was grown in elevated beds 0.8 m wide covered with plastic mulch. Row spacings were 1.8 m.

The trial was set out in a randomised block design with four treatments and five replicates (for layout see Appendix 1). Blocks of treatments were imposed over 4 adjacent rows. Blocks were separated by 10 m along the row. The crop was sprayed with herbicide to desiccate it on the 4/1/96 (see plate 8). The trellising was removed on the 8/1/96 in the morning (see plate 9) and the treatments were imposed in the afternoon. The four treatments were :

- bare ground where all plant material and plastic mulch had been removed, but the soil remained undisturbed;
- plastic mulch only remaining, all plant material removed;
- plastic mulch and stumps of plants remaining, where aerial parts of the plants were removed;
- all plant material and plastic mulch remaining.

Once treatments were imposed, emergence traps were erected over the rows (see plate 10). These traps were 0.75 m x 0.75 m x 1 m and comprised of a metal frame covered with a black leafminer proof mesh.

This mesh was tested prior to the start of the trial to make sure that leafminer moths were not able to get through it. Seven male pupae were placed in a plastic container with a hole cut in the lid. The mesh of the traps was then used to cover the hole in the container. A 1 m length of PVC pipe was taped securely to the top of the mesh covered container and a pheromone lure hung at the other end of the pipe. The end of the pipe with the pheromone lure was covered with a sleeve of fine gauze to catch any moths that made their way through the mesh.

Delta pheromone traps with the inside bottom surface covered with a sticky coating were constructed and hung from the top of the metal frame within each trap to catch male moths. Replications 1 and 2 had covers put over the traps on the 9/1/96 and replications 3,4 and 5 had their covers put in place on the 10/1/96. The traps were checked approximately every 2 days and any leafminer caught removed from the sticky surface of the trap. Weather information was obtained from a weather station approximately 400 m from the trial site and is detailed in Appendix 3. ANOVA was performed on cumulative numbers of moths emerged from the cages at 24 and 34 days using the QDPI RANB Computer statistical package. Data were transformed using $\sqrt{x+1/2}$

RESULTS

1. Pheromone Trapping Studies

Evaluation of Different Reservoir Waterlevels in Vertical Pheromone Traps

For both of the trials undertaken, no significant differences were found between any of the treatments. Results of an ANOVA for each trial can bee seen in Appendix 2. Table 1 shows the mean moth catches for each treatment in both of the trials.

Table 1 - Mean numbers of moths caught in traps with different water levels in trials 1 and 2.

Treatment	Trial 1 mean number of moths*	Trial 2 mean number of moths*
1/4	27.77a[+]	2.10a
1/2	19.56a	1.76a
3/4	17.43a	3.98a
Full	17.58a	5.76a

*equivalent means backtransformed

[+]In each column numbers followed by the same letter are not significantly different at the 5% level.

Aging of Standard Lures Used for Pheromone Trapping

The results of the t-tests carried out on data collected in the lure aging trial showed no significant differences between new and aged lures when lures were 2, 4, 6, 7 weeks old. Table 2 below show the mean number of moths caught in each treatment on each occasion that the trial was run.

Table 2 - Mean moth numbers caught with new, 2, 4, 6, 7 and 8 week old Agrisense lures.

Week of Trial	Mean number of moths caught with aged lure (±SD)	Mean number of moths caught with fresh lure (±SD)	t value	Probability
2	124.00 (60.43)	87.20 (36.11)	1.17	0.2761
4	83.60 (18.02)	43.20 (49.13)	1.73	0.1442
6	243.50 (16.68)	55.25 (165.42)	2.26	0.1067
7	53.00 (31.51)	17.50 (31.51)	2.15	0.1060
8	27.75 (33.2)	5.00 (2.16)	1.37	0.2637

Evaluation of an Experimental Agrisense Lure

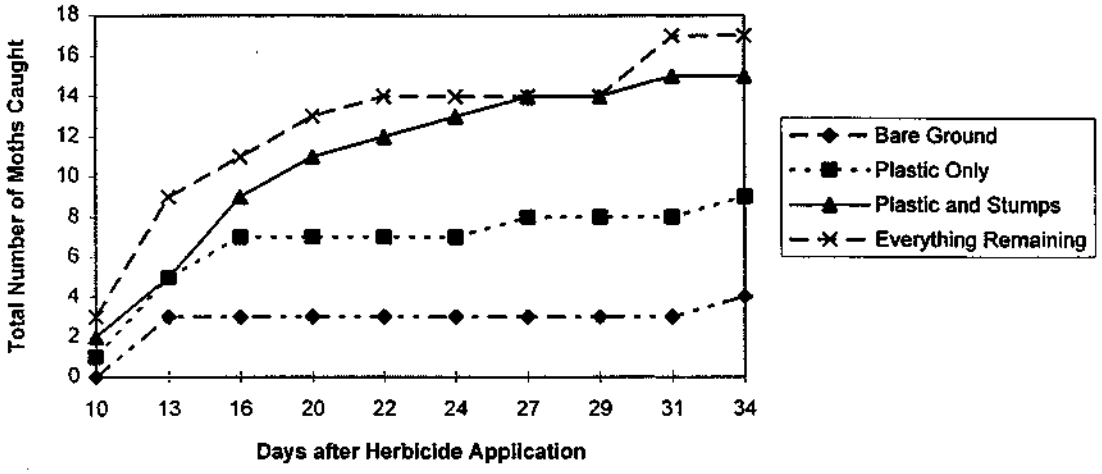
The traps baited with experimental lures containing the analogue did not catch any leafminer moths. The traps baited with standard Agrisense lures that these were compared to caught an average of 138.4 moths. As a clear difference was found no statistical analysis was performed.

2. Emergence Trapping

The small trial done to determine if moths were able to get through the mesh of the emergence trial showed that none were able to. Male moths emerged from pupae in the container covered by the mesh and died in the same container without making it through the mesh to the pheromone lure.

The cumulative numbers of moths from every cage for each treatment are presented in Graph 1. From this graph it can be seen that after 24 days there is a leveling off of the number of moths emerging. However, there is another increase in the cumulative numbers of moths emerged from day 31.

Graph 1 : Cumulative Number of Moths Emerged in Each Treatment in Emergence Trapping Trial



Significant differences at the 5 % level were found between treatment 1 (Bare Ground) and treatment 3 (Plastic and Stumps remaining) and between treatment 1 and treatment 4 (Everything Remaining) at days 24 and 34 (Table 3). At 24 days treatments 1 and 4 were significantly different at the 1% level

Table 3 : Mean cumulative numbers of moths emerged from different treatments at days 24 and 34.

Treatment	Mean cumulative number of moths emerged by day 24*	Mean cumulative number of moths emerged by day 34*
Bare Ground	0.471a[+]	0.617a
Plastic Only	1.163ab	1.580ab
Plastic and Stumps	2.506b	2.682b
Everything Remaining	2.711b	3.333c

*equivalent numbers backtransformed

[+]numbers followed by the same letter in each column are not significantly different at the 5% level

Results of an ANOVA at 24 and 34 days can be seen in Appendix 2

DISCUSSION

1. Pheromone Trapping Studies

Evaluation of Different Reservoir Waterlevels in Vertical Pheromone Traps

The pheromone trap catches in both trials indicated a large variation in the distribution of leafminer moths within the fields where the trials were carried out. In the first trial, carried out in the tomato block, traps that were 1/4 full caught the most moths on average. This trend was reversed in the second trial however, with the full traps averaging a higher catch than any other treatment. However, no significant differences were found between any of the treatments. These results suggest that there is no relationship between the waterlevel in the pheromone trap and the number of moths caught in that trap.

As there is no relationship between waterlevel and trap catch efficiency, evaporation changing the water level in a trap will not alter trap efficiency. As stated in the introduction, hot conditions can change trap waterlevels significantly. The vertical traps used in these trials have deep water reservoirs, meaning that it will take longer for them to dry up as compared to horizontal pheromone traps. This means that vertical pheromone traps may be left for a longer time before clearing without fear of reducing trap catches. Also, the trials indicate that it is not critical that water is of a uniform depth in traps within a field or experiment.

The variation of the pest within a field has implications for the use of pheromone traps as a monitoring tool. Currently tomato growers (or a consultant paid by that grower), generally place several traps around the perimeter of a crop. This practice may not give an accurate estimate of what population is actually present in the field. From a research point of view, variation of this type would need to be accounted for, possibly through experimental design and replication, when an experiment involving the use of pheromone traps was conducted.

Through experimental means it may be possible to determine the sources of variation of moth distribution within a field. It would be necessary to investigate if position in the field itself, the traps or time were sources of variation. This would show where traps should be put in the field and how many traps were needed. Foot (1979) reported that distribution of leafminer foliage mining intensity within a field tends to be non random. She reported that areas of high intensity occurred on the edges of blocks facing the prevailing wind. This seems consistent with pheromone trap catches in all trials reported on here. Traps positioned closer to the edge of the field generally caught more moths.

Aging of Standard Lures Used for Pheromone Trapping

Agrisense-BSC Limited recommend that leafminer lures be replaced every 6 to 8 weeks (Anon, 1992). The trials that were undertaken in this project show no significant differences in mean moth numbers from traps baited with new and old lures. This suggests that the attractiveness of the lure does not diminish until they are more than 8 weeks old.

Very high variation in trap catch was once again found in all trials undertaken to investigate the effect of age on lure attractiveness. For example when lures were 6 weeks old traps with new lures caught an average of 55.25 moths whereas traps with old lures caught an average of 243.5 moths. There was no significant difference between these averages. The mean number of moths for traps baited with old lures was made larger due to two high counts of 483 and 208 moths per trap. Each of these traps were located at the end of separate rows of pheromone traps, possibly meaning they had a larger area from which moths were attracted. Ideally, to overcome problems such as these traps should be located up to 100 m apart. Unfortunately, this was not possible as there are no tomato blocks large enough to allow for this.

There was a trend apparent in the data obtained suggesting the aged pheromone lures attracted more male moths than did fresh lures. This trend is apparent in all trials carried out on lures 2, 4, 6, 7 and 8 weeks old. There is no clear explanation for this trend. It is possible that it was due to the variation experienced in the field and was still apparent regardless of randomisation. Increased replication may help overcome this situation. Another possibility is that although fresh lures were still attractive to moths the concentration of pheromone that they released was slightly too strong and therefore they were not as attractive as aged lures. Drew (1982) states that for Queensland fruit fly high concentrations of an pheromone often have a repellency action.

When considering how long a pheromone lure may remain attractive, climatic influences should be taken into account. This trial was carried out at the hottest time of the year in Bundaberg (weather data is shown in Appendix 3). It would be expected that the pheromone would be released faster from the lure than at cooler times of the year. Therefore lures should last at least 8 weeks at any time of the year.

Evaluation of an Experimental Agrisense Lure

Trials undertaken by Agrisense in Egypt indicated that the analogue was almost as attractive to moths as the pheromone usually used (E. Casagrande, pers. comm., 1996). The analogue being used by Agrisense in the experimental lure proved not to be attractive

to leafminer moths when a trial was carried out in a commercial block of tomatoes in Bundaberg.

There are two possibilities why the lures containing the analogue did not catch any leafminer moths. The first possibility is that no analogue was impregnated into the lure. However, testing the lures to determine if analogue is present is beyond the scope of this project. The second possibility is that the analogue does not attract leafminer moths. Enzo Casagrande of Agrisense suggests the possibility of two different strains of the insect in Egypt and Australia (E. Casagrande, pers. comm., 1996). Unal *et al* (1993) reported that Maa (1986) found that for diamondback moth (*Plutella xylostella* (L)) the ratio of the pheromone blend which provides maximum male catch was different in strains from Taiwan, Japan and Canada. It is possible that leafminer moths in Egypt are attracted to the analogue but Australian leafminer moths are non responsive, perhaps requiring a chemical with a slightly different structure to induce a response.

2. Emergence Trapping

This trial showed that removal of tomato crops as soon as possible after desiccation has the potential to reduce the number of leafminer that emerge from an area. Significantly fewer leafminer moths emerged from treatments where all plant material was removed than from treatments where plant material remained. This supports local consultants' policy of crop hygiene and quick crop removal post harvest (J. Hall, pers. comm., 1995).

The length of time leafminer moths may emerge from tomato crop land was also shown in this trial. The number of moths emerging from all treatments leveled off after 24 days (Graph 1). However, there was a second phase of emergence after 31 days. This second increase comes after any leafminer present in the trap at the start of the trial, regardless of what stage they were in, should have developed into the adult stage. The average daily temperature for the time this trial was run was approximately 27°C. At this temperature Horne and Horne (1991) found that leafminer take approximately 23 days to develop form egg to adult. Assuming that male moths are attracted to the pheromone source soon after they emerge from pupae, there are three possible explanations for this second phase of emergence. Firstly, that moths are breeding within the emergence traps. This would mean that male and female moths are mating and the females, as they are not trapped in the pheromone trap, are laying eggs within the cage. It does not seem likely that moths were able to breed in the cages. The only plant material within cages was dried out and dead by this stage and no alternative food source was available. The second possibility is that moths were able to enter the traps from outside, possibly through a small unnoticed hole in the cage. These moths did appear fresh and undamaged however, and did not look as if they had forced themselves through a small opening. Mesh of the cage was tested to make sure moths were not able to get through it before the trial was set up and again after the end of the trial. This second test took place in an area where there was a

know leafminer population. An emergence trap was erected over ploughed soil in proximity to the eggfruit crop used in pheromone trapping studies. No moths were caught in the pheromone trap after 3 days. Finally, some leafminer entered some state of quiescence which extended the duration of their development. No reports of such behaviour were found in the literature. Rothschild (1986) states that there is no evidence of true diapause even under temperatures generally too low for development This possibility seems unlikely, as temperatures and humidities during the period of the trial were very high (Appendix 3) which should speed up not slow down development.

Based on the results of this study, a production break at the time of the year when the project was undertaken would need to be at least 54-56 days long. Moth emergence leveled off after 24 days. In further observations taken from the trial after the end of the experiment, no more moths were found to emerge after 34 days. Briese (1980) found that at 24°C adult moths lived for approximately 20 days. Therefore a break of 54-56 days would allow for the emergence of moths from old cropping ground and for these moths to die without finding a suitable host on which to oviposit.

The process of erecting emergence traps over possible hosts will have practical application for further study in determining host plants for leafminer as well as for other insects. Any insect that responds to a know pheromone may be investigated in this way, particularly if its sex ratio is close to 1:1. For leafminer, emergence traps could be erected over possible hosts such as other Solanaceous crops or weeds. This would help determine if having that particular plant present in proximity to a tomato growing area would offer an alternate host. If other plants are found that are hosts, it would be necessary to remove them if a break in production was attempted as a management strategy.

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REFERENCES

Anon. (1992) *Recommendations for the Use of Phthorimaea operculella Pheromone Trapping System* Agrisense-BCS Limited.

Briese, (1980) Characterisation of a laboratory strain of the potato moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae). *Bulletin of Entomological Research* **70**: 203-212.

Carde, R. I. and Elkinton, J. S. (1984) Field Trapping with Attractants : Methods and Interpretation pp 111-129 *In*: Hummel H. E. and Miller J. A. (eds) *Techniques in Pheromone Research*. Springer-Verlag: New York, Berlin, Heidelberg, Tokyo.

Drew, R.A.I. (1982) Fruit Fly Collecting pp 129-139 *In:* Drew, R.A.I., Hooper, G.H.S. and Bateman, M.A. *Economic Fruit Flies of the South Pacific Region* Queensland Department of Primary Industries: Brisbane.

Foot, M.A. (1979) Bionomics of the potato tuber moth, *Phthorimaea operculella* (Lepidoptera : Gelechiidae), at Pukekohe. *New Zealand Journal of Zoology* **6:** 623-636

Haines, C.P. (1977) *The potato tuber moth, Phthorimaea operculella (Zeller): a bibliography of recent literature and a review of its biology and control on potatoes in the field and in store*. Report of the Tropical Products Institute (London) G112

Hargraves, J.R. and Cooper, L.P. (1979) Insecticides for the control of tomato grub, *Heliothis armiger* (Hubner), and potato moth, *Phthorimaea operculella* (Zeller), in tomatoes. *Queensland Journal of Agricultural and Animal Sciences* **36**: 141-146

Horne, P. (1994) Biology and Management of potato moth (tomato leafminer) pp 47-49 *In: Workshop Report : Tomato Pest Management* Cooperative Research Centre for Tropical Pest Management, Brisbane, Australia.

Horne, P.A. and Horne, J.A. The effects of temperature and host density on the development and survival of *Copidosoma koehleri*. *Entomologia Experimentalis et Applicata* **59**: 289-292

Kay, I.R. (1993b) "Insecticidal Control of *Helicoverpa* spp. and *Phthorimaea operculella* on Tomatoes" pp 154-157 *In*: Corey S. Dall D. Milne W. (1993) (eds) *Pest Control and Sustainable Agriculture* CSIRO: East Melbourne.

Kay, I.R. (1993b) *Investigations on Phthorimaea operculella management in tomatoes at Bundaberg.* Final Report on projects funded by the Bundaberg District Fruit and Vegetable Growers' Association and the Horticultural Research and Development Corporation, 1990/91 and 1991/92 Department of Primary Industries.

Kay, I.R. and Walton, M.P. (1994) *Workshop Report : Tomato Pest Management* Cooperative Research Centre for Tropical Pest Management, Brisbane, Australia.

Maltby, J. E. (1995) Tomatoes - Fresh pp 289-292 *In*: Coombs B. *Horticulture Australia The Complete Reference on the Horticultural Industry* Morscope Publishing Pty Ltd: Australia.

Raman, K.V. (1988) Control of Potato Tuber Moth *Phthorimaea operculella* with Sex Pheromones in Peru. *Agriculture, Ecosystems and Environment* **21:**85-99.

Rothschild G. H. L. (1986) The Potato Moth - An Adaptable Pest of Short Term Cropping Systems. pp 145-162 *In*: Kitching R. L. (ed.) *The Ecology of Exotic Animals and Plants. Some Australian Case Histories.* J. Wiley: Brisbane.

Trivedi, T.P. and Rajagopal, D. (1992) Distribution, biology, ecology and management of potato tuber moth, *Phthorimaea operculella* (Zeller) (Lepidoptera : Gelechiidae): a review. *Tropical Pest Management* **38** 279-285.

Unal, I., Mohamed, M., Hong, L.W. and Rahman S.A., (1993) Evaluation of synthetic sex pheromones for suppressing diamondback moth, *Plutella xylostella* (L) pp 293-295 *In:* Corey S. Dall D. Milne W. (eds) *Pest Control and Sustainable Agriculture* CSIRO East Melbourne, Australia.

Appendix 1 - Experimental Design

1. Evaluation of Different Reservoir Waterlevels in Vertical Pheromone Traps - Trial 1

1/2	3/4	Full	1/4
Full	1/4	3/4	1/2
1/4	Full	1/2	3/4
3/4	1/2	Full	1/4
1/4	3/4	1/2	Full

2. Evaluation of Different Reservoir Waterlevels in Vertical Pheromone Traps - Trial 2

3/4
1/4
1/2
Full

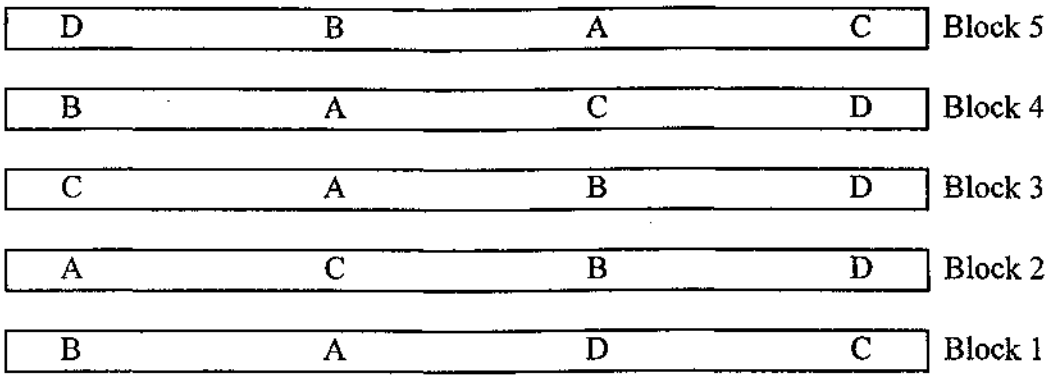
1/4
1/2
Full
3/4

1/4
3/4
Full
1/2

1/2
Full
3/4
1/4

3/4
1/4
1/2
Full

3. Emergence Trapping Trial



Treatments - A - Bare ground - All plant material and plastic removed.
B - Plastic only - All plant material removed (including stumps).
C - Plastic and stumps - Aerial plant parts only removed.
D - Everything remaining - All plant material, plastic and trash remains.

Appendix 2 - Tables from Statistical Analyses

Table 1 - ANOVA for Waterlevel Trial 1

Source	df	MS	F
Replicates	4	1.55996	3.35
Treatments	3	0.210759	0.45
Error	11	0.466208	

Table 2 - ANOVA for Waterlevel Trial 2

Source	df	MS	F
Replicates	4	1.08095	2.11
Treatments	3	0.799775	1.56
Error	11	0.512691	

Table 3 - ANOVA for Emergence Trial - 24 Days

Source	df	MS	F
Replicates	4	0.185054	1.11
Treatments	3	0.7316272	4.38
Error	12	0.167212	

Table 4 - ANOVA for Emergence Trial - 34 Days

Source	df	MS	F
Replicates	4	0.326456	1.49
treatments	3	0.792607	3.61
Error	12	0.219410	

Appendix 3 - Weather Data

Month	Date	Max Temp °C	Min Temp °C	Rainfall mm	Relative Humidity %
December	11	31	19	0.4	84
	12	25	20	34.0	91
	13	26	16		68
	14	26	16		
	15		17		
	16	30			
	17	31			
	18	37	18		
	19	33	23	3.6	
	20	32	21		
	21		22		
	22		18		
	23				
	24				
	25				
	26	28	17		
	27	28	21	18.8	
	28	29	21		
	29				
	30				
	31				
January	1	30			
	2	29.5	21		72
	3	29	24		77
	4	27	24		92
	5		21		84
	6				
	7	29.5			
	8	30	21		84
	9	29	24		92
	10	30	25		78
	11		24		78
	12				
	13				
	14	29.5			
	15	28.5	17		56
	16	29	18		56
	17	28	20		61
	18	29.5	19		64
	19		20		64

	20				
	21	30			
	22	30	21		59
	23	30	22		64
	24	30	21	18.4	92
	25		21	trace	
	26				
	27				
	28	33			
	29	32	20	7.0	77
	30	33	22		72
	31	34	25		72
February	1	34	26		61
	2		22		65
	3				
	4	33			
	5	32	22		65
	6	33	21		65
	7	33	22		65
	8	33	22		65
	9		24		72
	10				
	11	33			
	12		17	4.0	45

Plate 1 : *Phthorimaea operculella*, tomato leafminer moth. (Source QDPI)

Plate 2 : Leaf damage to a tomato plant caused by leafminer. (Source QDPI)

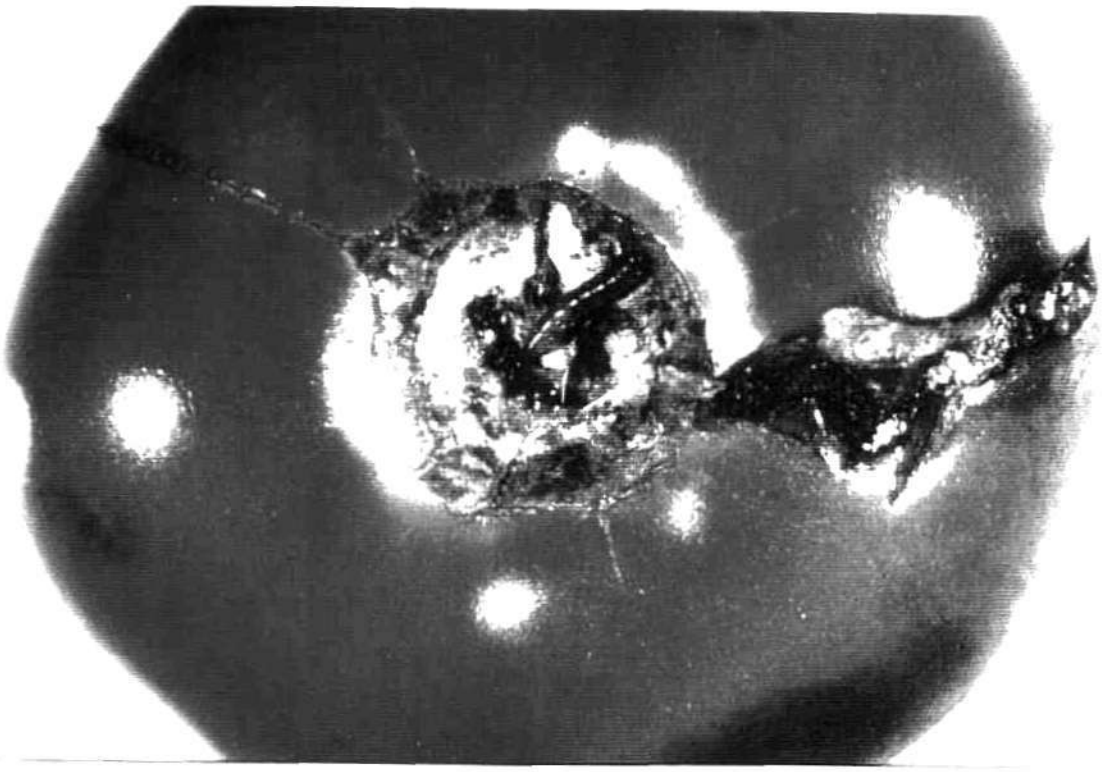


Plate 3 : Damage to tomato fruit caused by leafminer and a leafminer larvae. (Source QDPI)

Plate 4 : Damage to tomato fruit cause by leafminer. (Source QDPI)

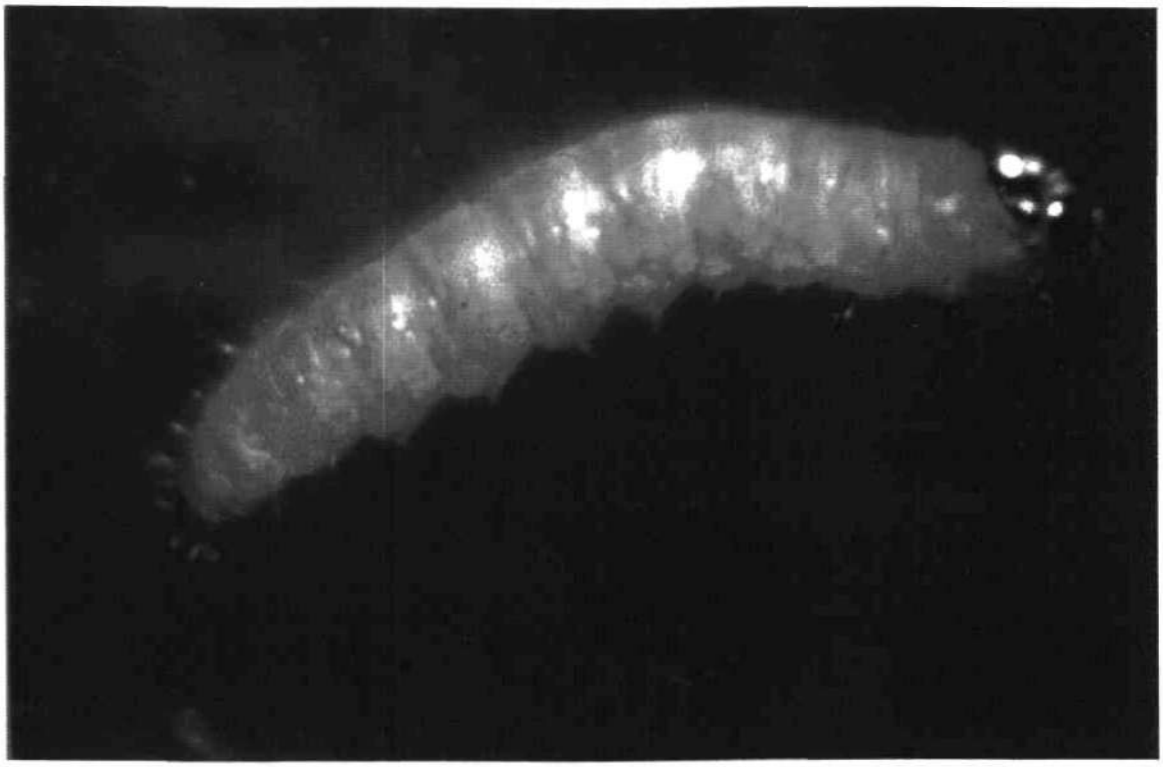


Plate 5 : *Phthorimaea operculella*, tomato leafminer larvae. (Source QDPI)

Plate 6 : The vertical pheromone trap used in pheromone trapping studies.

Plate 7 : Pheromone traps in the eggfruit block, Dr Mays Crossing Road.

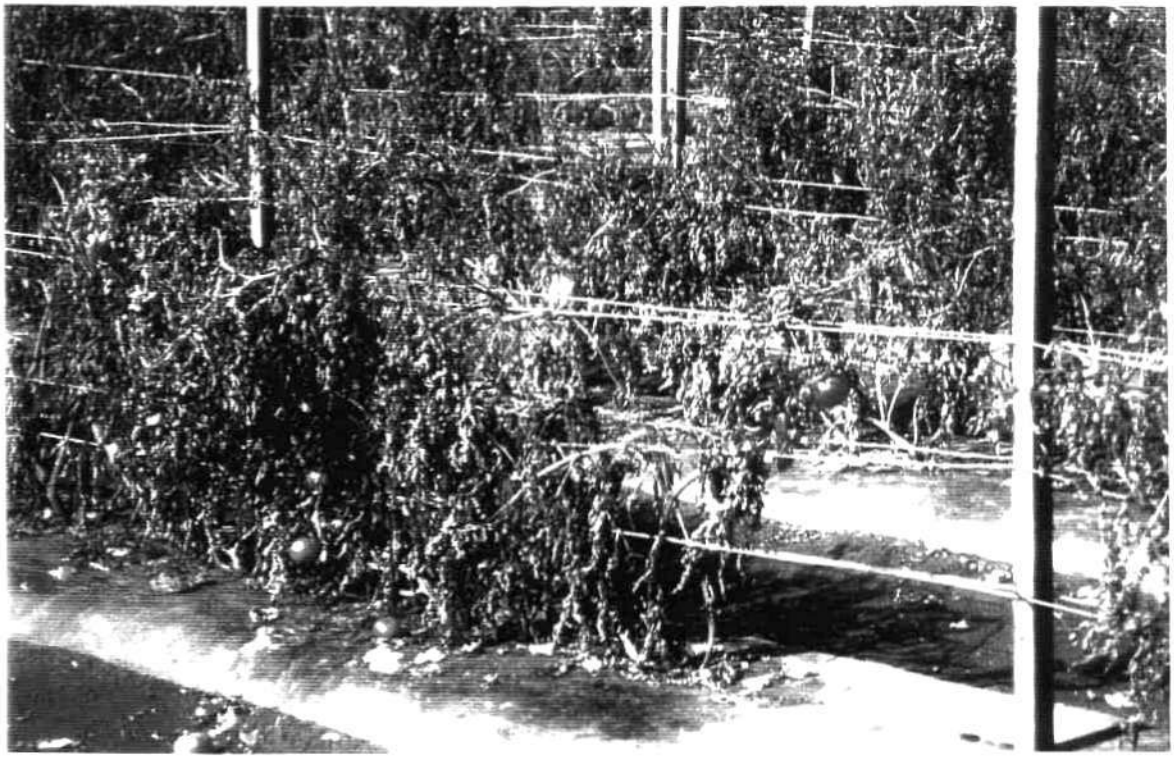


Plate 8 : A desiccated tomato crop.

Plate 9 : A desiccated tomato crop with the trellis wires pulled.

Plate 10 : The emergence cages used in post-harvest emergence trapping investigations.

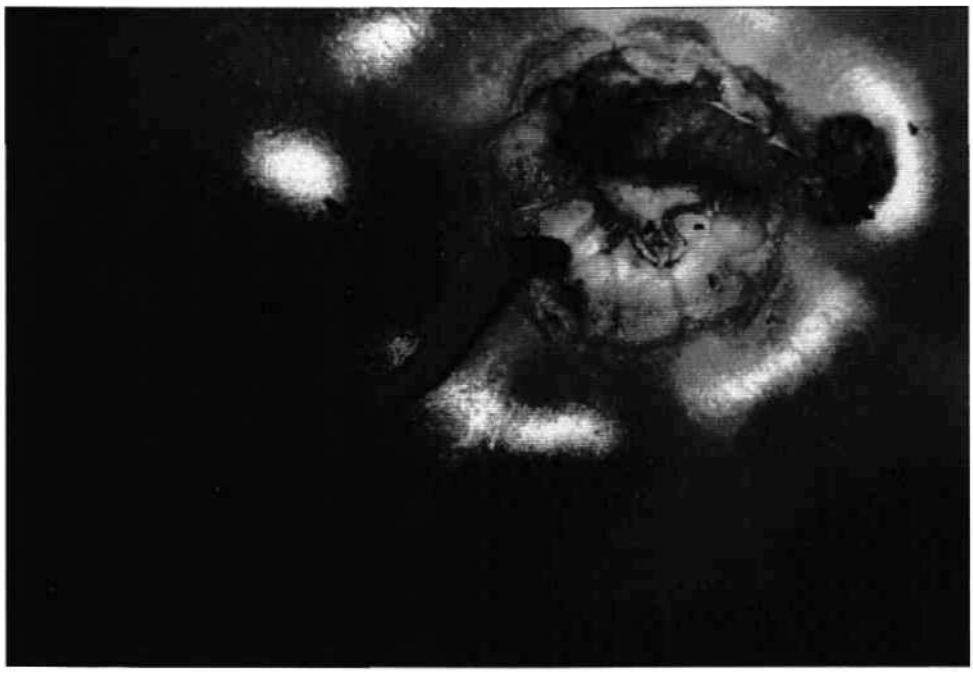
Appendix 2 – Final Report for Vacation Scholarship

Suitability of solanaceous weeds as host plants for tomato leafminer, *Phthorimaea operculella* (Zeller).

Leonard Ford

February 1998

Suitability of solanaceous weeds as host plants for tomato leafminer, *Phthorimaea operculella* (Zeller).



Leonard Ford

Presented at the CRC for Tropical Pest Management

The University of Queensland

27 February, 1998

Abstract

The tomato leafminer, *Phthorimaea operculella*, is a pest of a range of solanaceous crops and weeds. *P. operculella* was recently identified as one of the major arthropod pests of the Queensland tomato industry. The extension of the production season in the major tomato producing areas may have contributed to the increase in leafminer populations and pest status. A series of statewide production breaks are to be introduced to interrupt the food supply of leafminer and thus reduce its pest status. Whether leafminer can shift to alternative weed hosts during a production break will be an important factor in the success of the production break. Sampling of alternative hosts undertaken in the field has found only one weed host to date common thornapple (*Datura stramonium*). Other weed-hosts listed in literature do occur but have not been infested by leafminer. The aim of the project was to determine whether the more common weeds are or are not hosts of leafminer. This was determined by measuring the larval development on *Amaranthus dubies*, *Datura ferox*, *Cestrum parqui*, *Solanum nigrum* and *Lycopersicon esculentum*, and the oviposition preference of adults on *D. ferox*, *L. esculentum* and *S. nigrum*. The results of the experiments indicate that *A. dubies*, *C. parqui*, and *S. nigrum* may not be suitable as alternative host plants as suggested in the literature. *D. ferox* was found to be suitable host of leafminer with the ability to sustain leafminer populations and importantly, increase larval development time relative to that on *L. esculentum*. This may have important implications for proposed production breaks.

1. Introduction

The tomato leafminer, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae), is a cosmopolitan pest of solanaceous crops and infests a range of solanaceous weeds; the moth has also been referred to as potato tuber moth, potato tuber worm and tobacco leafminer.

The leafminer's centre of origin is thought to be in the eastern Andes, where its main solanaceous hosts – potato and tobacco – are thought to have originated and where it is associated with a particularly prolific complex of specific parasites which maintain its population at low levels (Rothschild, 1986). The species is now distributed in tropical, subtropical and warm-temperate zones throughout the world wherever its cultivated and wild hosts occur (Rothschild, 1986). Host plants include potatoes (*Solanum tuberosum*), tomatoes *(Lycopersicon esculentum*) and chilli *(Capsicum annum*) (Table 1).

Table 1. Some alternative host plants of tomato leafminer[1].

Scientific name[2]	Common name	Status
Amaranthus dubies[3]	Amaranth	Weed
Capsicum annum	Chilli	Crop
Cestrum parqui	Green cestrum	Weed
Datura ferox	Fierce thornapple	Weed
Datura stramonium	Common thornapple	Weed
Lycopersicon esculentum	Tomato	Crop
Nicandra physalodes	Apple of Peru	Weed
Nicotiana amplexicaulis	Tobacco	Crop
Solanum nigrum	Blackberry nightshade	Weed
Solanum tuberosum	Potato	Crop

[1]adapted from Das and Raman (1994)
[2]Family Solanaceae unless otherwise stated
[3]Amaranthaceae

Through human activities, particularly the transportation of potato tubers in ships' stores, leafminer has become widely distributed. Leafminer was almost certainly introduced into Australia in this way, probably as early as the late eighteenth century (Rothschild, 1986). By the 1900s leafminer was recorded as a pest in all areas of Australia, due to the transportation of infested potato tubers for seed and food.

Adult moths (Figure 1) rest in concealed sites under leaves and clods of soil or other debris during the day. The females lay their eggs after sunset, either singly or in small groups on the soil near the base of their host plants or on the undersides of the leaves. After hatching from eggs laid on foliage, larvae tunnel into the leaves and feed within the mesophyll tissues forming irregular blotch or tunnel mines (Figure 2). The larvae pass through four instars, all of which are spent within the host plant and more than 80% of the total intake of plant material is attributable to the final instar (Figure 3) (Rothschild, 1986). Before pupation, larvae leave their feeding sites and construct a protective silken cocoon among leaf litter or on the aerial parts of the host plant within a rolled-up leaf. The duration of the life cycle (egg to adult) in spring-summer ranges from 35-60 days (Rothschild, 1986).

Feeding damage caused by leafminer greatly reduces the quality and market value of the tubers (Das and Raman, 1994) and tomato fruit and creates sites for infection by microorganisms, sometimes causing complete destruction of the produce.

Tomato leafminer was recently identified as one of the three major arthropod pests of the Queensland tomato industry (Kay and Walton, 1994) along with heliothis and two-spotted mite. Although leafminer has been present in Queensland since at least the 1970s, it was not until the mid-1980s that leafminer was regarded as only a sporadic pest of tomatoes. Since the 1970s the production season has extended in the Bundaberg, Bowen and Lockyer Valley regions. The Bowen region, situated in the dry tropics, specialises in the winter production of fruit and vegetables (tomato being the main crop) and by the mid-1980s became continuous in its production of tomatoes. In the mid to late 1980s the Bundaberg region moved to year

Figure 1. Adult tomato leafminer, *Phthorimaea operculella* (Zeller) (Source QDPI).

Figure 2. Leaf mines caused by feeding larvae of tomato leafminer (Source QDPI).

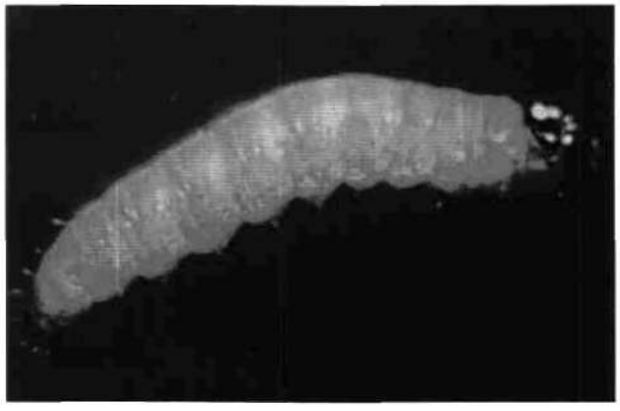


Figure 3. Fourth instar of tomato leafminer.

round production. This was stimulated by the availability of cold-tolerant varieties. Production patterns in the Lockyer Valley have also changed; during the 1980s producers began growing through the summer, starting in August and producing through to the first frosts. The extension of the production season in the major tomato producing areas may have contributed to the increase in leafminer populations and pest status.

The lack of a production break has been recognised by the industry. In Bowen, pheromone traps were catching less than 40 moths per week in 1992 (Kay and Walton, 1994). The number increased to more than 110 moths per week in 1993 following the decision of some growers to maintain production throughout the season (Kay and Walton, 1994). At the end of 1993, a voluntary production break of one month was introduced which was followed by a dramatic decrease in the number of leafminer caught (Kay and Walton, 1994). Whether the decline in leafminer numbers was due to improved cultural practices or some other factors is unknown.

At a recent Tomato Pest Management Workshop (Kay and Walton, 1994) it was suggested that a series of statewide production breaks should be introduced to interrupt the food supply of leafminer and thus reduce its pest status in each of the major production areas (Bowen, Bundaberg and the Lockyer Valley). The necessary duration of the production-break in each area is unknown and a recommendation for research to fill this gap in knowledge was identified as a priority in the Action Plans arising from this meeting.

In order to develop a production-break strategy, it was necessary to produce a generalised leafminer development model. The generic insect population model "DYMEX", developed at the Cooperative Research Centre for Tropical Pest Management, has been used to produce a model for tomato leafminer populations using published data and pheromone trap/temperature data from Bundaberg, Bowen and Victoria. It will be essential to consider additional factors in the strategy. These factors include sources and movement of leafminer populations, their potential breeding sites and possible alternative host plants (such as weeds).

Weeds may limit crop production, directly by competing for abiotic factors required for growth (water and nutrients) and indirectly by acting as reservoirs for pest organisms affecting crops (Bendixen, 1979). The impact of weeds competing directly with tomato crops in Queensland has declined since the introduction of plastic mulch in the 1980s (Kay and Walton, 1994). However the ability of weeds to indirectly limit crop production by acting as reservoirs for pests, such as leafminer is still unknown.

This project assessed whether solanaceous weeds act as alternative hosts thereby harbouring leafminer populations in crop-free periods, and are therefore a potential source of crop reinfestation. The literature lists numerous alternative hosts, most of which are in the family Solanaceae. However sampling of alternative hosts undertaken in the Lockyer Valley and at Bundaberg has found only one weed host to date - common thornapple (*Datura stramonium*). Other weed-hosts listed in literature do occur but no leafminer eggs or larvae have been found on them. Why then are they are not being recorded as hosts in the current survey?

It is possible that many of these listed weeds are not hosts or at least are not good hosts of leafminer in Queensland. The aim of the project was to determine whether the more common weeds are or are not hosts of leafminer. The establishment, development and survival of tomato leafminer on weed hosts was measured by placing eggs onto potted plants and measuring relevant developmental parameters. Oviposition preference by adults on weeds and tomatoes was determined by caging moths with plants in two-choice situations. Plants were then examined for the presence of eggs.

2. Materials and Methods

2.1 Insect rearing

2.1.1 Adults

Adult moths were held in plastic cylinder containers (10 x 10cm), with the top covered by a cloth mesh and sealed with a rubber band. The moths were allowed to mate and lay eggs. On top of the cloth mesh was a 90mm diameter piece of filter paper; this gave the moths a favourable surface on which to lay eggs and a means of collecting the eggs. On a daily basis, filter paper with eggs attached to them were removed from the mesh and placed in a petri dish. The petri dish was sealed with parafilm, labelled with the date of egg lay and transferred to an incubator (27°C). Adults were provided with fresh filter paper and fed pure honey. The honey was applied with a 5ml syringe; approximately 4 or 5 drops were placed on the mesh between the filter paper and the edge of the container.

2.1.2 Eggs

Eggs were held in the incubator until just prior to hatching (approx. 4 days at 27°C). This was determined by noting the change in colour of the eggs. Newly-laid eggs are clear in colour, change to dark orange and then black prior to hatching. When eggs had turned dark orange, they were transferred to potatoes as a food source for hatching larvae.

2.1.3 Larvae

A potato was washed and its surface perforated to provide points of entry for the emerging neonate larvae. The potato was then placed into a plastic cylinder container (10 x 10 cm) on a wire frame that enables air flow past all surfaces of the potato and delays rotting. In the bottom of the container a 1cm layer of coarse sand was provided for the larvae to construct a pupal case. The filter paper with eggs attached was placed between the wire frame and the potato for hatching making it easier for emerging larvae to locate the food source. The filter paper was removed the next day.

2.1.4 Pupae

Larvae complete 4 instars before pupation (this takes approximately two weeks). The 4th instar larvae usually make cocoons in the coarse sand at the bottom of the container but sometimes in the frass on the surface of the potato. Pupae were transferred daily from the containers to petri dish(es), which were sealed and stored at 4°C. When a sufficient number of pupae were collected (approx. 50), they were transferred to containers (as described in section 2.1.1) to complete pupation in the incubator (pupal development takes an average of 8 days).

2.2 Plants

Plants for experiments were obtained by (1) seeds that were sown in a glasshouse at Department of Primary Industries (DPI), Indooroopilly and (2) field collection of seedlings found around tomato and potato fields in the Lockyer Valley. Seeds of solanaceous weeds were provided by Ian Walker, Bowen Horticultural Research Station, and included: *Datura ferox, D. stramonium, D. tatula, Nicandra physalodes, Nicotiana forsteri, Physalis primosa, Solanum mauritianum, S. nigrum,* and *S. torvum*. Prior to sowing, the seeds were placed in hot water and left to soak for 24 hours to stimulate germination (I.Walker, pers. comm.). *D. ferox* seeds germinated in sufficient numbers (10-20) and grew to usable size (approx. 20cm in height) after transplanting to individual pots (diameter 15cm), to be used in the second replicate of oviposition experiment (see section 2.3). Seeds of the other species failed to germinate or germinate in sufficient numbers to be used in the experiments.

Seedlings of amaranth (*A. dubies*), green cestrum (*C. parqui*), common thornapple (*D. stramonium*), Apple of Peru (*N. physalodes*) and Brazilian nightshade (*S. nigrum)* were collected from around tomato and potato fields in the Lockyer Valley. The seedlings were transplanted into pots (diameter 15cm), fertilised with "Aquasol" (0.4g/L, Hortico, Victoria) and watered daily in a glasshouse at DPI, Indooroopilly. Tomato (*L. esculentum*) seedlings were purchased from a nursery and were also potted on, fertilised and watered in the glasshouse.

Shortly after transplanting, the weeds *D. stramonium*, *N. physalodes* and *S. nigrum* were infested with two-spotted mites (*Tetranychus urticae*) and bean spider mites (*T. ludeni*). A 'Domestic Pack' of predatory mites (*Phytoseiulus persimilis*) purchased from BioProtection, Warwick, Queensland, were released as a control measure. Each pack contains a minimum of 2000 predators in all life stages including eggs, on 30 bean stalks, each stalk holding three leaves. These leaves were separated giving about 90 single leaves containing the predators which were spread throughout the infested weeds and other test plants. The predatory mites were unable to control the pests probably due to the extremely large size of the pest population. Aphids (various species) also attacked the *S. nigrum* plants. A 'Domestic Pack' of green lacewings (*Mallada signata*) were purchased from Bugs for Bugs, Mundubbera, Queensland and released to control the aphids and spider mites. Each pack contains 300 eggs of *M. signata,* which were then distributed on the foliage of the infested weeds and other test plants. The eggs hatched approx. 24 hours later and after four days, the larvae of the green lacewing reduced the aphids and the *T. urticae* and *T. ludeni* populations to a point where no pests could be found on the plants.

These pest infestations caused the defoliation of the field-collected seedlings of *D. stramonium* and *N. physalodes*, rendering the plants unusable in the experiments. Seedlings of the weed, fierce thornapple (*D. ferox*), was collected from an unused field plot at the DPI, Indooroopilly and transplanted to the glasshouse, and potted up, watered and fertilised as described earlier. *D. ferox* is a close relative of *D. stramonium* and also listed as an alternative host (see Table 1), and was used in the experiments along with the remaining test-plants: *A. dubies*, *C. parqui*, *S. nigrum* and *L. esculentum*.

2.3 Oviposition preference of *P. operculella*

Pupae of *P. operculella* were collected and placed into individual vials containing a drop of honey on the inside of the lid as a food source for emerging adults. The sex of individual moths could be determined under light microscopy and mating conditions controlled. The

number of male and female moths that emerged each day was counted and released into a cage (15 x 15 x 20cm) overnight for mating (up to 30 moths at a time were held overnight). The cage was constructed from a metal frame covered with cloth mesh. One side was made as a sleeve so moths could be released and recaptured. After approx. 18 hours the moths were recaptured and placed into individual vials. To obtain enough female moths to set up a single replicate (i.e. 15 moths), female moths were collected over two consecutive nights.

To determine the oviposition response of mated female moths, 15 females were released into three cages (5 moths per cage) containing two different potted plants, in a glasshouse at DPI, Indooroopilly. The cages (40 x 40 x 70 cm) were constructed using two wire arcs as the frame and covered in cloth mesh, with one side which could be sealed with pins serving as an entry point (see Figure 4). The cages contained a choice of *L. esculentum* vs *D. ferox*, *L. esculentum* vs *S. nigrum* and *D. ferox* vs *S. nigrum*. The female moths were allowed to oviposit for three days, after which the plants were removed and the number of eggs laid on the plants were counted. The moths were recaptured at the end of the replicate. This experiment was to be replicated six times, however, due to problems outlined in section 2.1 and time constraints only two replicates were able to be performed.

The temperature in the glasshouse was monitored using a thermohydrograph. The average daily temperature was 29°C with minimum of 24°C and a maximum of 35°C.

2.4 No-choice Testing (Larval feeding tests)

To determine if *P. operculella* could establish and develop on the test plants, eggs that had been laid on filter paper (as described in section 2.1.2) were attached, 1 egg per leaf, to the leaves of the plants using egg white to attach the filter paper to the leaves (Figure 5). In each replicate 20 eggs were placed on each plant species (5 eggs on 4 plants of each species). Plants used in the first replicate were: *A. dubies, C. parqui, D. ferox, L. esculentum* and *S. nigrum*. After hatching, the number of larvae that established on each plant was recorded (i.e. presence of mines) and the development of each larva was monitored on a daily basis.

Figure 4. Cages constructed for two-choice oviposition preference experiments. Each cage contained two potted plants.

Figure 5. Eggs of *Phthorimaea operculella* that had been laid on pieces of filter paper were attached to the leaves of each plant species (5 eggs on 4 plants of each species). The establishment, mortality, and development rate from hatching to 4th instar larva were recorded daily.

Ants were observed entering the leaf mines to remove larvae in the first replicate. A second replicate was therefore set up, this time using *D. ferox, L. esculentum* and *S. nigrum* (there were insufficient plants of *A. dubies* and *C. parqui* for a further replicate and results from the first replicate indicated that *P. operculella* did not establish or feed on these plants). The potted plants were placed in trays of water to exclude ants and 'Ant-rid' (Boron 9.24g/kg, Bryant and May, Victoria) was placed on the bench with plants to attract and kill ants.

Temperature was monitored in the glasshouse using a thermohydrograph. The average daily temperature was 28.5°C with minimum of 22°C and maximum of 35°C.

Differences in larval development time on *D.* ferox and *L. esculentum* were analysed using a two-sample *t*-test (assuming equal variances).

3. Results

3.1 Oviposition preference of *P. operculella*

The results shown are for one replicate only. Only three eggs were collected on six plants in the second replicate.

Similar numbers of eggs were laid on *L. esculentum* and *D. ferox* when moths were given a choice between the two plants (Table 2). No eggs were laid on *S. nigrum* when the moths had a choice between it and *L. esculentum* or *D. ferox*.

Table 2. Number of eggs laid by *P. operculella* on *L. esculentum*, *D. ferox* and *S. nigrum* in two-choice host plant tests.

Plants	Eggs laid
L. esculentum vs *D. ferox*	24 vs 19
L. esculentum vs *S. nigrum*	29 vs 0
D. ferox vs *S. nigrum*	60 vs 0

3.2 No-choice Testing (Larval feeding tests)

P. operculella larvae hatched but failed to establish on *A. dubies* and *C. parqui* (Table 3). Larvae successfully hatched on *D. ferox*, *L. esculentum* and *S. nigrum*, with approximately three quarters of the hatched larvae establishing and forming mines in each case. Since mortality was very high in this replicate (due to ants and unknown factors) comparison of developmental rates was not possible.

Table 3. The level of hatching and establishment of *P. operculella* on *A. dubies*, *C. parqui*, *D. ferox*, *L. esculentum* and *S. nigrum*.

Plant	Eggs	Hatched	Established	%mortality[1]
A. dubies	20	6	0	0
C. parqui	20	12	0	0
D. ferox	20	17	12	83
L. esculentum	20	16	12	83
S. nigrum	20	14	11	82

[1]due to ants and other unknown factors

Unlike the first replicate, *P. operculella* larvae hatched but failed to establish on *S. nigrum* in the second replicate (Table 4). The larvae successfully hatched and established on *D. ferox* and *L. esculentum*. The number of larvae that hatched on *D. ferox*, *L. esculentum* and *S. nigrum* in the second replicate ranged from 8 to 12, this was lower than the first replicate where for the same plants the range was from 14 to 17. Establishment of larvae on *D. ferox* was higher in the second replicate, while *L. esculentum* establishment was the same in both replicates. The development time of the larvae was longer on *L. esculentum* than on *D. ferox*. A *t*-test performed on the development times of larvae on *D. ferox* and *L. esculentum* indicated that the means of the development times were significantly different ($t_{0.05,9}$=3.04, 0.01<P<0.02).

Table 4. The percentage of *P. operculella* larvae that hatched and established on *D. ferox*, *L. esculentum* and *S. nigrum* and the development time of larvae (hatching to 4th instar).

Plant	Eggs	Hatched	Established	Development time (days)[1]
D. ferox	20	10	10	7.67
L. esculentum	20	12	9	12
S. nigrum	20	8	0	0

[1]average number of days from hatching to 4th instar.

4. Discussion

Although insufficient replicates were run for each of the experiments to make firm conclusions, some trends were evident. In the experiment designed to examine oviposition preference in *P. operculella*, female moths laid no eggs on *S. nigrum* when given the choice between it and *L. esculentum* or *D. ferox*. This matched previous observations of no eggs found on *S. nigrum* in the field. The moths may have found *L. esculentum* and *D. ferox* more attractive for oviposition than *S. nigrum* because of visual and/or chemical cues. Conversely

the moths may have been repelled by visual and/or chemicals cues from *S. nigrum*. There appeared to be little difference in oviposition preference between *L. esculentum* and *D. ferox*.

In the experiment designed to examine oviposition preference in *P. operculella*, the plants used in the second replicate were smaller than those used in the first replicate and this may have affected the oviposition behaviour of the moth. The size of the plants relative to the cage may have affected the level of attraction of the plants to the moths, and resulted in reduced oviposition on the plants.

In the first replicate of the experiment to determine if *P. operculella* could establish and develop on the test plants, larvae established on *D. ferox*, *L. esculentum* and *S. nigrum* but failed to establish on *A. dubies* and *C. parqui*. Both *A. dubies* and *C. parqui* are listed in the literature as alternative hosts (Das and Raman, 1994). However the definition of "host" in Das and Raman's review is: "indicates feeding by the insect on the plant species to complete an entire generation, feeding sighted in the field or feeding observed in the laboratory." It is possible that *A. dubies* and *C. parqui* were recorded as hosts because of observed feeding (leafmining) in the field on these plants for a short time, after which the larvae may have moved onto another plant or died. In the experiment to determine if *P. operculella* could establish and develop on the test plants, the observations were longer (i.e. 14 days). If a stricter definition of a suitable host were to be applied, for example, establishment and development of *P. operculella* on the plant species, then it is possible that *A. dubies* and *C. parqui* may not be regarded as suitable hosts.

Due to high mortality of larvae caused by ants, a second replicate was set up using plants that larvae had established on in the first replicate. Larvae again established on *D. ferox* and *L. esculentum* but this time failed to establish on *S. nigrum*.

S. nigrum plants used in the first replicate had been damaged by mite and aphid infestations while the plants used in the second replicate were young, undamaged regrowth. *S. nigrum*

plants used in the second replicate more closely simulated those found in the field, where no *P. operculella* eggs or larvae have been observed. The young, undamaged leaves of *S. nigrum* (in the experiment and in the field) may be unable to support larval development because of the chemistry of leaf, that is, the plant may produce compounds that are toxic to the developing larvae. Larvae may have been able to establish on *S. nigrum* in the first replicate because the leaves were damaged by mite and aphid infestations therefore altering the chemistry of the leaves and enabling *P. operculella* to establish.

The results of the two experiments indicate that *P. operculella* will not oviposit on *S. nigrum* if a more preferred host is available (eg. *D. ferox* or *L. esculentum*) and that larvae will not establish and develop on *S. nigrum*. These results are consistent with roadside surveys and field trials of solanaceous weeds and crops conducted by Cameron *et al* (1997) that found that *P. operculella* failed to infest *S. nigrum*. This indicates that *S. nigrum* may not be a suitable host of *P. operculella* as suggested by Das and Raman (1994).

The results from the experiment to determine if *P. operculella* could establish on the test plants indicate that larvae develop faster on *D. ferox* than on *L. esculentum*. Why did the larvae develop faster on *D. ferox* than on *L. esculentum*? Two possible theories to explain this outcome are:

(1) the plant chemistry of *D. ferox* was beneficial to larvae development i.e. could change the physiology or metabolism of the larvae. Thus the plant that the larvae are placed on may have a "direct" effect on the larval development;

(2) the type of host plant that insects were reared on might "condition" insects to develop better on certain plants. If *D. ferox* and potato (which the insects were reared on) have similar plant chemistry it may be that the larvae were better "adapted" to feed on *D. ferox* than on *L. esculentum*. Thus the plant that the larvae are reared on may have a "indirect" on larval development.

To test which theory may be correct an experiment could be conducted. The experiment would involve rearing *P. operculella* on *D. ferox* and potato and then placing larvae on plants they had been reared on as well as on those on which they had not been reared (i.e. larvae reared on *D. ferox* would be placed on *D. ferox* and potato plants and vice versa) and their development times recorded. The possible outcomes of the experiment would be:

(i) Larvae developed faster on the plant on which they were reared, suggesting that theory (2) may be correct.

(ii) Larvae developed faster on one plant (regardless of which plant they were reared on), suggesting theory (1) is correct.

(iii) Larvae developed the same on both plants, also suggesting that theory (2) is correct, i.e. larval development times are faster on *D. ferox* and potato than *L. esculentum*.

The results of the experiments performed for this project could have important implications for the proposed production-breaks. The implications are (1) *P. operculella* can survive on weeds (especially *D. ferox*) during a production break, therefore it will be important to remove weeds that can sustain *P. operculella* populations; (2) *P. operculella* can develop faster on *D. ferox* (and possibly other weed species), therefore it will be even more important to remove those weeds that can sustain *P. operculella* populations and even increase populations more rapidly (than populations infesting *L. esculentum*). The density of these weeds and their distance from tomato fields will be important factors in the determining the likely impact of the production-break.

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References

Bendixen, L.E. (1979) Weeds serving as reservoirs for organisms affecting crops. *Proceedings 7th Asian-Pacific Weed Sci. Soc. Conf.*, Ohio, USA, pp 211-212.

Cameron, P.J., Gatland, A.M., Walker, G.P. and Wigley, P.J. (1997) Alternative host plants as refugia for diamondback moth and potato tuber moth. *Proc. 50th N.Z. Plant Protection Conf.,* Auckland, New Zealand, pp 242-246.

Das, G.P. and Raman K.V. (1994) Alternate hosts of potato tuber moth, *Phthorimaea operculella* (Zeller). *Crop Protection.* **13,** 83-86.

Kay, I.R. and Walton, M.P. (1994) *Workshop Report: Tomato Pest Management* Cooperative Research Centre for Tropical Pest Management, Brisbane, Australia.

Rothschild, G.H.L. (1986) The Potato Moth - An Adaptable Pest of Short Term Cropping Systems. pp 145-162 *In*: Kitching R.L. (ed.) *The Ecology of Exotic Animals and Plants. Some Australian Case Histories*. J. Wiley: Brisbane.