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Simulation modelling as a decision support in developing a sterile insect-inherited sterility release strategy for *Eldana saccharina* (Lepidoptera: Pyralidae)

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Abstract

A user-friendly simulation tool for determining the impact of the sterile insect technique/inherited sterility technique (SIT/IS) on populations of the African sugarcane stalk borer, *Eldana saccharina* Walker (Lepidoptera: Pyralidae) is described in this paper. The simulation tool is based on a spatio-temporal model. The design of the simulation tool is such that it is applicable for use in a number of pest/crop and pest control scenarios. It uses 4 interacting subsystems (pest species population dynamics, crop dynamics, environmental dynamics and economics) within a specified spatial domain. Furthermore, the spatial domain describes the layout of the agricultural crop (position, size, shape, crop age and variety of the different fields contained within the crop area). The pest species population subsystem describes *E. saccharina* population dynamics (but is designed to also include population dynamics of other pest species) under the influence of the IS technique. The *E. saccharina* module developed utilizes mean-field and spatio-temporal models, and includes dynamics of all *E. saccharina* life stages under the influence of the control measure. Only temperature and damage caused by *E. saccharina* are currently included as variables in the sugarcane dynamics subsystem. This subsystem estimates stalk length as a function of time and temperature, and sucrose percentage as a function of damage caused by *E. saccharina* boring. Interaction between *E. saccharina* population growth and sugarcane growth is described by a decreasing s-shaped density-dependent mortality function—the older the cane, the higher the carrying capacity (more food resources) and corresponding infestation and damage levels. The only environmental factor considered as an independent variable in the environmental dynamics subsystem is temperature. Possible extensions to this subsystem are discussed. The economics subsystem developed includes the estimation of the recoverable value, percentage, expected revenue and the cost of control. No other farm expenditures are taken into account. As such only profit or loss expected from applying the IS technique is estimated. The profit or loss is defined as the increase in revenue expected less the cost of applying a pest control measure. An example of using the simulation tool is presented in the context of a real field scenario of a simulated SIT/IS program against *E. saccharina* at a pilot site near the Eston area of KwaZulu-Natal, South Africa.

Key Words*:* inherited sterility; African sugar cane borer; pest population dynamics; sugarcane dynamics; environmental dynamics and economics; pest control; sugarcane field configurations

Resumen

Se describe en este documento una herramienta de simulación fácil de uso para determinar el impacto de la técnica del insecto estéril/esterilidad heredada (TIE/EH) en las poblaciones del barrenador del tallo de caña de azúcar de África, *Eldana saccharina* Walker (Lepidoptera: Pyralidae). La herramienta de simulación se basa en un modelo espacio-temporal. El diseño de la herramienta de simulación es aplicable para su uso en una serie de escenarios de plagas/cultivos y de control de plagas. Se utiliza 4 subsistemas que interactúan (dinámica de las poblaciones de especies de plagas, dinámica de los cultivos, dinámica del medio ambiente y economía) en un dominio espacial determinado. Por otra parte, el dominio espacial describe el diseño del cultivo agrícola (posición, tamaño, forma, edad del cultivo y la variedad de diferentes campos dentro del área del cultivo). El subsistema de población de las especies de plagas describe la dinámica de poblaciones de *E. saccharina* (pero está diseñado para incluir la dinámica de poblaciones de otras especies de plagas) bajo la influencia de la técnica de EH. El módulo de *E. saccharina* desarrollado utiliza un modelo del promedio de campo y de espacio-temporal e incluye la dinámica de todos los estadios de vida de *E. saccharina* bajo la influencia de la medida de control. Sólo la temperatura, y los daños causados por *E. saccharina* se incluyen actualmente como variables en el subsistema de la dinámica de la caña de azúcar. Este subsistema estima la longitud de tallo como una función del tiempo y la temperatura, y el porcentaje de sacarosa como una función del daño causado por los barrenadores *E. saccharina*. Se describe la interacción entre el crecimiento de la población de *E. saccharina* y el crecimiento de la caña de azúcar por una función decreciente de mortalidad dependiente de la densidad en forma de s — la mayor edad de la caña, la mayor será la capacidad de carga (más recursos alimentarios) y nivel de daño e infestación correspondiente. El único factor ambiental considerado como una variable independiente en el subsistema de la dinámica del medio ambiente es la temperatura. Se discuten las posibles ampliaciones de este subsistema. El subsistema de la economía desarrollado incluye la estimación del valor recuperable, porcentaje, los ingresos previstos y el costo del control. No se tomaron los otros gastos agrícolas en cuenta. Como tal, se estimó sólo el resultado del periodo esperado de la aplicación de la técnica EH. Se define la ganancia o perdida como el aumento de los ingresos esperado menos el costo de la aplicación de una medida de control de plagas. Se presenta un ejemplo del uso de la herramienta de simulación en el contexto de un escenario de campo real de un programa de TIE simulada contra *E. saccharina*

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en un sitio piloto cerca del área de Eston de KwaZulu-Natal, Sudáfrica.

Palabras Clave: esterilidad heredada; barrenador de caña de azúcar de África; dinámica de la población de plagas; dinámica de la caña de azúcar; dinámica del medio ambiente y la economía; control de plagas; configuraciones de campo de caña de azúcar

Sugarcane, *Saccharum* spp. (Poales: Poaceae), a major agricultural crop in South Africa, is grown by approximately 24,000 registered sugarcane growers. Its production area is in the northeastern side of the country, extending from Northern Pondoland in the Eastern Cape Province through the coastal belt and midlands of KwaZulu-Natal, to the Mpumalanga lowveld (SASA 2015). The South African Sugarcane Research Institute (SASRI) plays an important role in identifying, developing and promoting sound and sustainable environmental practices within the industry (in line with national legislation and international requirements). Best management practices have been developed for many agricultural practices over the last few decades. However, a major concern that remains is the sustainable management of pest species of sugarcane, such as the African sugarcane stalk borer, *Eldana saccharina* Walker (Lepidoptera: Pyralidae) (Carnegie 1974). SASRI has developed an integrated pest management (IPM) system for sugarcane farmers against it, which focusses on sound farming practices such as the use of resistant sugarcane varieties, pre-trashing, the removal of old stalks in the field, improved soil management, responsible use of insecticides and the use of uninfested seed cane pieces (Webster et al. 2005; Rutherford 2015). Although the current IPM practices promote lower infestation levels, they can often be unsuccessful in preventing infestations, especially in areas prone to high infestations or during drought. Newer interventions, such as biological control (Conlong 1997, 2001), habitat management (Conlong & Rutherford 2009) and the sterile insect technique (SIT) (Barnes et al. 2015) applied to this species are currently in the research phase, and ways to incorporate these approaches into the IPM system are under consideration.

This paper reports on the design and application of a user-friendly simulation tool, which may aid the current efforts to manage the *E. saccharina* problem that will include an IS component. The objective is to introduce a basic platform whereby the effectiveness of various pest management strategies that include the IS technique in native *E. saccharina* populations may be investigated in sugarcane, using different scenarios, depending on various parameter values and heterogeneous landscapes. Determining effective pest management strategies by means of in-field experimentation can be a costly, labor- and time-intensive endeavor, and enough resources are not always available to conduct large-scale experiments. For this reason, simulation modelling is becoming an increasingly attractive alternative to assist in the design and development of IPM strategies. Although the current design of the simulation tool focusses on the IS technique, a framework for a computerised platform is developed which may be extended to a decision support system for use in an area-wide IPM program.

Simulation Design

Many mathematical and simulation models in agriculture tend to be developed in isolation, only focussing on one part of an agricultural ecosystem. The system proposed here consists of 4 interacting subsystems within a specified spatial domain, namely the pest species population dynamics, the sugarcane dynamics, the environmental dynamics and the economics subsystems, as illustrated in Fig. 1. The interaction between the subsystems is illustrated by means of arrows. Sugarcane pests cause damage to the sugarcane plant which, in turn, influences the plant growth and the revenue that may eventually be generated during harvesting time. The environment, which may include, for example, temperature, rainfall and soil type, influences plant growth which, in turn, influences the food resource available to the pest species. It is illustrated (in simplified terms) how these different modules may be integrated into a system that simulates the agricultural sugarcane ecosystem. More research is, however, required to thoroughly understand and model the interaction between these subsystems in a realistic manner, with the main challenge in modelling being the interaction between the different pest species and the host plant. The different subsystems are described in more detail in the sections that follow.

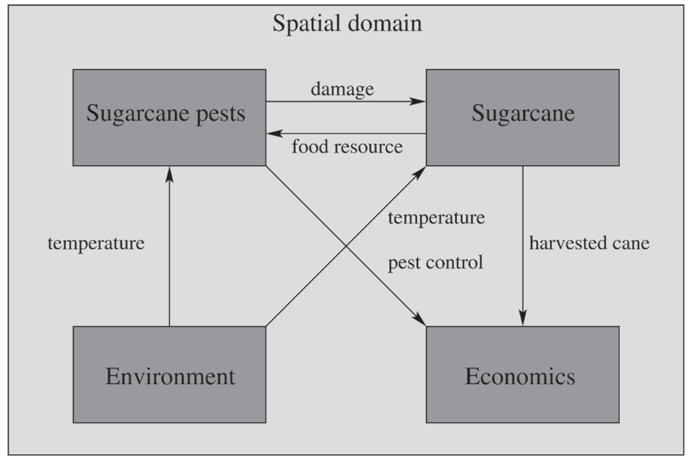

Fig. 1. The system designed for simulating pest species dynamics in sugarcane.

THE SPATIAL DOMAIN

The spatial domain on which the different subsystems are modelled, describes the layout of the agricultural crop—in this case different but adjacent sugarcane fields. The layout includes the position, size, shape, cane age and crop variety of the different fields contained within the sugarcane area, as well as the paths between the fields.

THE PEST SPECIES SUBSYSTEM

The most important pest species in South African sugarcane include stalk borers (of which *E. saccharina* is the most significant), soil pests (which include white grubs (Coleoptera) and nematodes (Nematoda)) and leaf feeders (which include various species of grasshoppers (Orthoptera) and thrips (Thripidae)). Mathematical models describing the population dynamics of the above-mentioned pest species (under the influence of certain control measures) may all be integrated in the pest species population dynamics subsystem as illustrated in Fig. 2. The interaction between the different species, i.e., the effect that 1 species may have on the population growth of another species, still needs to be understood more thoroughly in order to facilitate realistic attempts at integrating the different models. Environmental factors and food resources from the host plant influence population growth of the various species. These feed on different parts of the sugarcane plant, and therefore the sugarcane growth model will have to include information on the growth of roots, stalks and leaves. The total damage caused to the sugarcane plant may be described by a crop damage index, which may then be used in the sugarcane growth subsystem to translate the amount of damage to the percentage of sucrose lost. The total amount

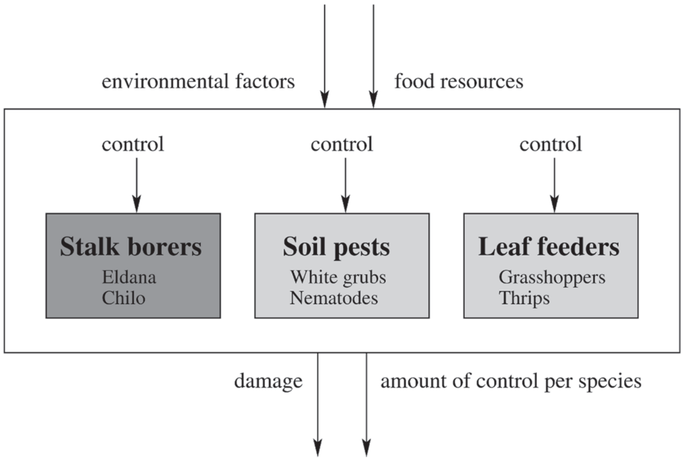

Fig. 2. The pest species subsystem which may include all the important pest species in South African sugarcane. The total damage caused by the various pest species may be estimated by such a system. Currently, only the *Eldana saccharina* module has been developed.

of control applied to the various pest species may be used by the economics subsystem to estimate the cost of the control measures.

As the simulation tool was developed to facilitate the SIT/IS research with respect to *E. saccharina*; the pest species subsystem currently only describes *E. saccharina* population dynamics (excluding all other pest species attacking sugarcane) under the influence of the IS technique (excluding all other control measures). The *E. saccharina* module developed utilizes the mean-field and spatio-temporal models of Potgieter et al. (2012, 2013), and includes the dynamics of all *E. saccharina* life stages under the influence of the IS technique as a control measure.

Earlier models in the literature on the SIT/IS are all based on geometric growth. Models that incorporated types of density regulation, as in the case of logistic growth, were proposed from the early 1970s onwards by, for example, Miller & Weidhaas (1974), Prout (1978) and Barclay (1980, 1982). Barclay & Mackauer (1980) were the first to propose a model in which the dynamics of the released sterile population was also described. Population movements in a SIT context have also been studied by, for example, Prout (1978) and Manoranjan & Van den Driessche (1986). However, limited examples of movement models exist in the literature (Barclay et al. 2005).

In line with the previously mentioned literature and also expanding on these models, the spatio-temporal model developed in this study considers all 5 life-stages of *E. saccharina* for both the fertile and inherited sterile population, with density-dependence in the larval stage. The dynamics of the released irradiated insects is also described, with dispersal of moths in the form of diffusion. Eleven subpopulations were therefore considered within a closed, simply connected, 2-dimensional spatial domain *S*, as illustrated in Fig. 3. Let $E_i(\underline{\xi},t)$ denote the densities (measured in e/100 stalks, i.e., number of borers per 100 stalks) of the 11 subpopulations at position $\underline{\xi} = [\xi_1, \xi_2]^T \in S$ and at time $t \in [0,\infty)$. The population vector $\underline{E}(\underline{\xi},t)$ is assumed to satisfy the reaction-diffusion equation

$$\frac{\partial \mathrm{E}\ (\underline{\xi},t)}{\partial x} = \underline{f}(\underline{\xi},t,\ \underline{\mathrm{E}}) + \nabla \cdot [\mathrm{D}(\underline{\xi})\nabla\underline{\mathrm{E}}\ (\underline{\xi},t)],$$

where $\underline{f}(\underline{\xi},t,\ \underline{E})$ contains as its i^{th} entry the number of the i^{th} subpopulation created during time t. More specifically,

$$f_1(\underline{\xi},t,\ \underline{\mathrm{E}}) = 0.5(\gamma(\underline{\xi},t)\lambda_f + \beta\rho(\underline{\xi},t)\lambda_s)E_9(\underline{\xi},t) - (\mu_F(t,\tau) + \alpha_E(t,\tau))E_1(\underline{\xi},t),$$

$$f_2(\underline{\xi},t,\ \underline{\mathrm{E}}) = 0.5\ (1-\beta)\rho(\underline{\xi},t)\lambda_s E_9(\underline{\xi},t) - (\mu_{\bar{n}}(t,\tau) + \alpha_E(t,\tau))E_2(\underline{\xi},t),$$

$$f_3(\underline{\xi},t,\ \underline{\mathrm{E}}) = \alpha_E(t,\tau)E_1(\underline{\xi},t) - (\mu_{L1}(\underline{\xi},t,\tau) + \alpha_{L1}\ (t,\tau))E_3(\underline{\xi},t),$$

$$f_4(\underline{\xi},t,\ \underline{\mathrm{E}}) = \alpha_E(t,\tau)E_2(\underline{\xi},t) - (\mu_{L1}(\underline{\xi},t,\tau) + \alpha_{L1}\ (t,\tau))E_4(\underline{\xi},t),$$

$$f_5(\underline{\xi},t,\ \underline{\mathrm{E}}) = \alpha_{L1}(t,\tau)E_3(\underline{\xi},t) - \big(\mu_{L2}(\underline{\xi},t,\tau)\big(1 + b(\underline{\xi},t)((E_5 + E_6)(\underline{\xi},t))\big) + \alpha_{L2}(t,\tau)\big)E_5(\underline{\xi},t)$$

$$f_6(\underline{\xi},t,\ \underline{\mathrm{E}}) = \alpha_{L1}(t,\tau)E_4(\underline{\xi},t) - \big(\mu_{L2}(\underline{\xi},\mathrm{v},\tau)\big(1 + b(\underline{\xi},t)((E_5 + E_6)(\underline{\xi},t))\big) + \alpha_{L2}(t,\tau)\big)E_6(\underline{\xi},t)$$

$$f_7(\underline{\xi},t,\ \underline{\mathrm{E}}) = \alpha_{L2}(t,\tau)E_5(\underline{\xi},t) - (\mu_p(t,\tau) + \alpha_p(t,\tau))E_7(\underline{\xi},t)$$

$$f_8(\underline{\xi},t,\ \underline{\mathrm{E}}) = \alpha_{L2}(t,\tau)E_6(\underline{\xi},t) - (\mu_p(t,\tau) + \alpha_p(t,\tau))E_8(\underline{\xi},t)$$

$$f_9(\underline{\xi},t,\ \underline{\mathrm{E}}) = \alpha_{L2}(t,\tau)E_7(\underline{\xi},t) - \mu_M(t,\tau)E_9(\underline{\xi},t)$$

$$f_{10}(\underline{\xi},t,\ \underline{\mathrm{E}}) = \alpha_{L2}(t,\tau)E_8(\underline{\xi},t) - \mu_M(t,\tau)E_{10}(\underline{\xi},t)$$

$$f_{11}(\underline{\xi},t,\ \underline{\mathrm{E}}) = \mathrm{r}(\underline{\xi},t) - \mu_5(t,\tau)E_{11}(\underline{\xi},t)$$

where λ_f and λ_s denote the egg laying rates of a fertile female mated with a fertile and partially fertile released male, respectively; $\gamma(\underline{\xi},t)$ and $\rho\ (\underline{\xi},t)$ denote the probabilities of a fertile egg being fertilized by a fertile or semi-fertile sperm at position $\underline{\xi}$ and time t, respectively; $\mu_E(t,\tau)$, $\mu_p(t,\tau)$, $\mu_M(t,\tau)$ and $\mu_S(t,\tau)$ denote the stage-specific mortality rates at time t at a temperature of τ degrees; and $\mu_{L1}(\underline{\xi},t,\tau)$ and $\mu_{L2}(\underline{\xi},t,\tau)$ denote the small and large larval mortality rates at position $\underline{\xi}$ and time t at a temperature of τ degrees. Furthermore, $\mathrm{b}(\underline{\xi},t)$ denotes the density-dependent mortality parameter; $\alpha_E(t,\tau)$, $\alpha_{L1}(t,\tau)$, $\alpha_{L2}(t,\tau)$ and $\alpha_p(t,\tau)$ denote the egg, larval and pupal maturation rates; and $\mathrm{r}(\underline{\xi},t)$ denotes the release rate at position $\underline{\xi}$ and time t. Finally, β denotes the fraction of eggs from the F_1 progeny of released partially fertile males that is fertile. The probabilities of fertilization, $\gamma(\underline{\xi},t)$ and $\rho(\underline{\xi},t)$, are derived using a method similar to that proposed by Berryman (1967), allowing for multiple matings, but in this case also allowing for semi-fertile males and an inherited sterile population. In this context, a fertile female, a released sterile female or an F_1 sterile female may either mate with a fertile male, a released semi-fertile male or an F_1 sterile male, resulting in 9 possible mating combinations. Furthermore, competitiveness as well as the proportion of residual fertility in the released population was accounted for in the probability calculations, in line with the models derived by Berryman (1967), Klassen & Creech (1971) and Barclay (1982, 2001). The probability of fertilization with a fertile sperm, $\gamma(\underline{\xi},t)$, is given by

$$\sum_{n=1}^{B} M_n \sum_{k=1}^{n} \binom{n}{\mathrm{k}} (-1)^{\mathrm{k}+1} P_{ff}(t)^{\mathrm{k}} \sum_{n=1}^{A} F_n \Big(1 - P_{im}(t) - (P^n_{rm}(t) - c_s P_{\mathrm{rm}}(t) - c_s P^n_{rm}(t))\Big)$$

where A and B denote the number of possible matings for males and females and M_n and F_n denote the fraction of males and females mating n times. Also, $\mathrm{P}_{\mathrm{ff}}(t)$, $\mathrm{P}_{\mathrm{im}}(t)$ and $\mathrm{P}_{\mathrm{rm}}(t)$ denote the probabilities of mating with a wild fertile female, an inherited sterile male and a released semi-fertile male at time t, respectively, and c_s denotes the competitiveness factor of released semi-fertile sperm compared to other sperm. Furthermore, the expressions

$$P_{rm}(t) = \frac{c_m m E_{11}(t)(1-q)}{0.5E_9(t) + c_m m E_{11}(t) + 0.6E_{10}(t)},$$

$$P_{im}(t) = \frac{0.6E_{10}(t)}{0.5E_9(t) + c_m m E_{11}(t) + 0.6E_{10}(t)},\ \text{and}$$

$$P_{ff}(t) = \frac{0.6E_{10}(t)}{0.5E_9(t) + c_f(1-m)E_{11}(t) + 0.4E_{10}(t)}$$

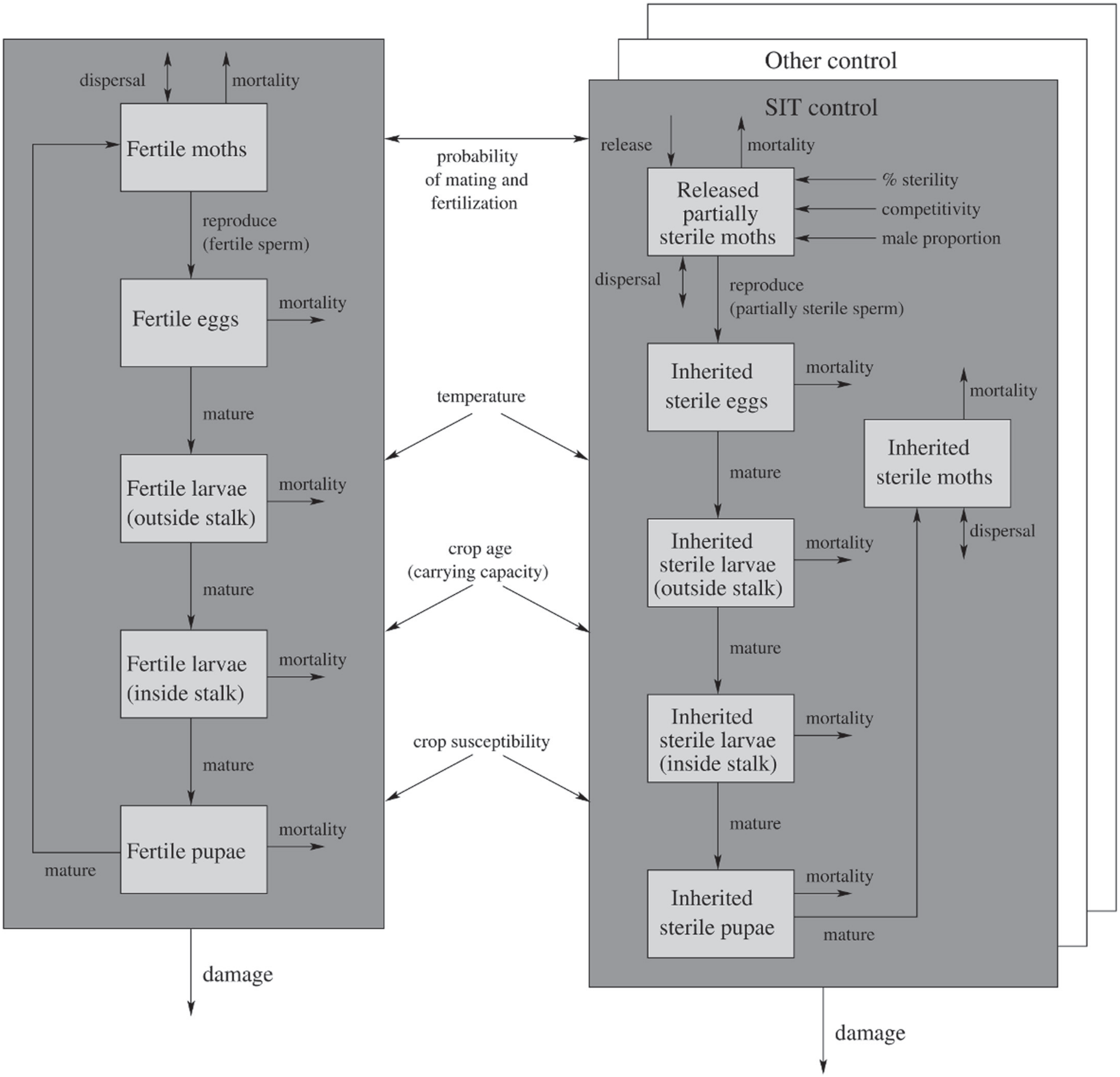

Fig. 3. The *Eldana saccharina* module developed in this study. The module describes the dynamics of all *E. saccharina* life stages under the influence of the SIT/IS technique. Other control measures may also be included, and are currently under investigation.

are assumed, where c_m denotes the competitiveness coefficient of released semi-fertile males, c_f denotes the competitiveness coefficient of released sterile females, *q* denotes the proportion of residual fertility within the released insect population and *m* denotes the male proportion in the released insect population. Equal proportions of males and females are assumed within the wild fertile population, whereas the F_1 sterile population is assumed to have a slight male bias. Furthermore, *m* may either be equal to 0, 1 or 0.5 depending on whether the released insects are female only, male only, or a combination of female and male, respectively. The probability of fertilization with a semi-fertile sperm, $\rho(\underline{\xi},t)$, is given by

$$\sum_{n=1}^{B} M_n \sum_{k=1}^{n} \binom{n}{k} (-1)^{k+1} P_{ff}(t)^k \sum_{n=1}^{A} F_n \left(P_{rm}^{n}(t) + c_s P_{\mathrm{rm}}(t) - c_s P_{rm}^{n}(t) \right).$$

The derivation of these probabilities was explained in detail by Potgieter et al. (2012).

THE SUGARCANE SUBSYSTEM

The sugarcane dynamics subsystem includes a simplified model of sugarcane dynamics, illustrated in Fig. 4. Sugarcane growth is influenced by a number of environmental factors, including temperature, rainfall and the type of soil (Bezuidenhout 2000). The damage caused by different sugarcane pest species also has an impact on sugarcane growth. Only temperature and damage caused by *E. saccharina* are currently included as variables in the sugarcane model. The model estimates the stalk length as a function of time and temperature, and

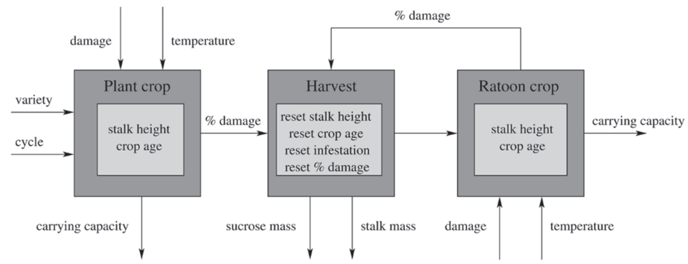

Fig. 4. A model representing sugarcane dynamics as currently implemented in the simulation tool for the field application of a SIT/IS strategy against *Eldana saccharina* in sugarcane.

sucrose percentage as a function of damage caused by *E. saccharina* boring. Interaction between *E. saccharina* population growth and sugarcane growth is described by a decreasing s-shaped density-dependent mortality function (Potgieter et al. 2013)—the older the cane, the higher its carrying capacity (more food resources) and corresponding infestation and damage levels. The stalk length (ℓ) at time $t + 1$ is estimated by the function $\ell(t + 1) = \ell(t) + 0.16(24)(-1.32+0.176(\tau - 10))$, which was obtained from the CANEGRO model (Inman-Bamber 1991; Bezuidenhout 2000), with temperature (t) as the only independent variable. Ideal growing conditions are assumed. A function for estimating sucrose (S) percentage at harvest time, is given by

$$S(\underline{\xi}) = \frac{-1.31\delta(\underline{\xi},t) + 84}{-5.78\delta(\underline{\xi},t) + 556},$$

where the numerator denotes the sucrose mass measured in g/stalk—while the denominator denotes the stalk mass also measured in g/stalk—as formulated by Potgieter et al. (2012) using data from a previous study conducted on sugarcane growth and yield at Gingindlovu, KwaZulu-Natal (Goebel & Way 2003). In this function, the sucrose and stalk mass are both influenced by the percentage internodes damaged, $\delta(\underline{\xi},t)$, in mature sugarcane at harvest time t at position $\underline{\xi}$, given by

$$\delta(\underline{\xi},t) = \frac{\sum_{j=0}^{t} \sigma(j)\left(E_5(\underline{\xi},j)+E_6(\underline{\xi},j)\right)}{\ell(\underline{\xi},t)},$$

where $\sigma(j)$ denotes the amount of larval feeding per larva on day j and where $\ell(\underline{\xi},t)$ denotes the average stalk length on day t at position $\underline{\xi}$. No explicit temporal models for sucrose (S), fiber (F) and non-fiber (N) content in cane is included in the model formulation—these values are instead estimated at harvest time only, using data from previous seasons. The harvesting of cane is included in the subsystem, albeit in very simplified terms—fields are assumed to be harvested at the end of a sugarcane cycle, at an age of either 12 or 24 mo, with harvesting assumed possible during any mo of the year. The closed-mill period between Nov and Apr is therefore not taken into consideration, nor are the *E. saccharina* infestation levels—a farmer would typically harvest a field when infestation and damage reach a certain level, which may be as early as 14–16 mo. Once a field is harvested, revenue is generated using the estimated values for S, F and N, and a new growth cycle is assumed to start immediately.

THE ENVIRONMENT SUBSYSTEM

The only environmental factor considered as an independent variable in the pest species population dynamics and sugarcane growth models implemented, is temperature. A valuable addition may be to include other environmental factors as additional variables, such as soil type, fertilizers applied (Morgan et al. 2015) and rainfall.

THE ECONOMICS SUBSYSTEM

Investigating the economic viability of a pest control measure is important from a farm owner's perspective. A pest control measure (or combination of control measures) is considered economically viable if the increase in revenue as a result of implementing the measure is greater than the cost involved in implementing the measure. The South African sugar industry has, since the start of the 2000/01 season, adopted the recoverable value (RV) payment system (Canegrowers 2002). The RV percentage is calculated by the formula

$$RV = S - dN - cF,$$

where S denotes the percentage of sucrose in cane delivered as before, d denotes the relative value of sucrose lost from sugar production per unit of non-sucrose and N denotes the percentage of non-sucrose in cane delivered. Furthermore, c denotes the loss of sucrose from sugar production per unit of fiber and F denotes the percentage of fiber in cane delivered. The economics module developed in this study includes the estimation of the RV percentage, expected revenue and the cost of control. The revenue, W, due to a farmer is calculated by

$$W = I_{rv} \sum_{\underline{\xi}} T(\underline{\xi}) \frac{RV(\underline{\xi})}{100},$$

where I_{rv} denotes the payment per RV percentage, and $T(\underline{\xi})$ denotes the average number of tons of sugarcane delivered at position $\underline{\xi}$, namely

$$0.13h_p(-5.78(\underline{\xi},t) + 556),$$

where h_p denotes the size of the habitat patch at position $\underline{\xi}$ (measured in ha), and assuming 130,000 sugarcane stalks per ha. The total cost, C, of a release strategy is given by

$$C = \sum_{j=0}^{t} K_r\Big(\sum_{\underline{\xi}} r(\underline{\xi},j)\Big) + \phi(j)h(K_e + K_f),$$

where $r(\underline{\xi},j)$ denotes the number of irradiated insects released at position $\underline{\xi}$ on day j and $\phi(j)$ denotes a Bernoulli variable which takes the value 1 if irradiated moths are released on day j, and 0 otherwise. Furthermore, h denotes the size of the release site in ha, and the cost of rearing and irradiating 1 moth, labor cost and transportation cost are denoted by K_r, K_e and K_f, respectively.

No other farm expenditures are taken into account, and as such only the profit or loss expected from applying the pest control measures (in this case the IS technique) are estimated. The profit or loss is defined as the increase in revenue expected, less the cost of applying a pest control measure.

Simulation Implementation

A first-order concept demonstrator of a computerized platform or simulation tool was implemented in Matlab, and included a graphical user interface. First, an algorithm for importing GIS shapefiles as matrix data structures was implemented in Matlab using its Mapping Toolbox (Mathworks 2013). A discretization of the domain was achieved by imposing a rectangular grid topology over the domain, as illustrated in Fig. 5. In order to perform simulations on the discretized domain, the rectangular grid topology was transformed to a matrix structure containing the

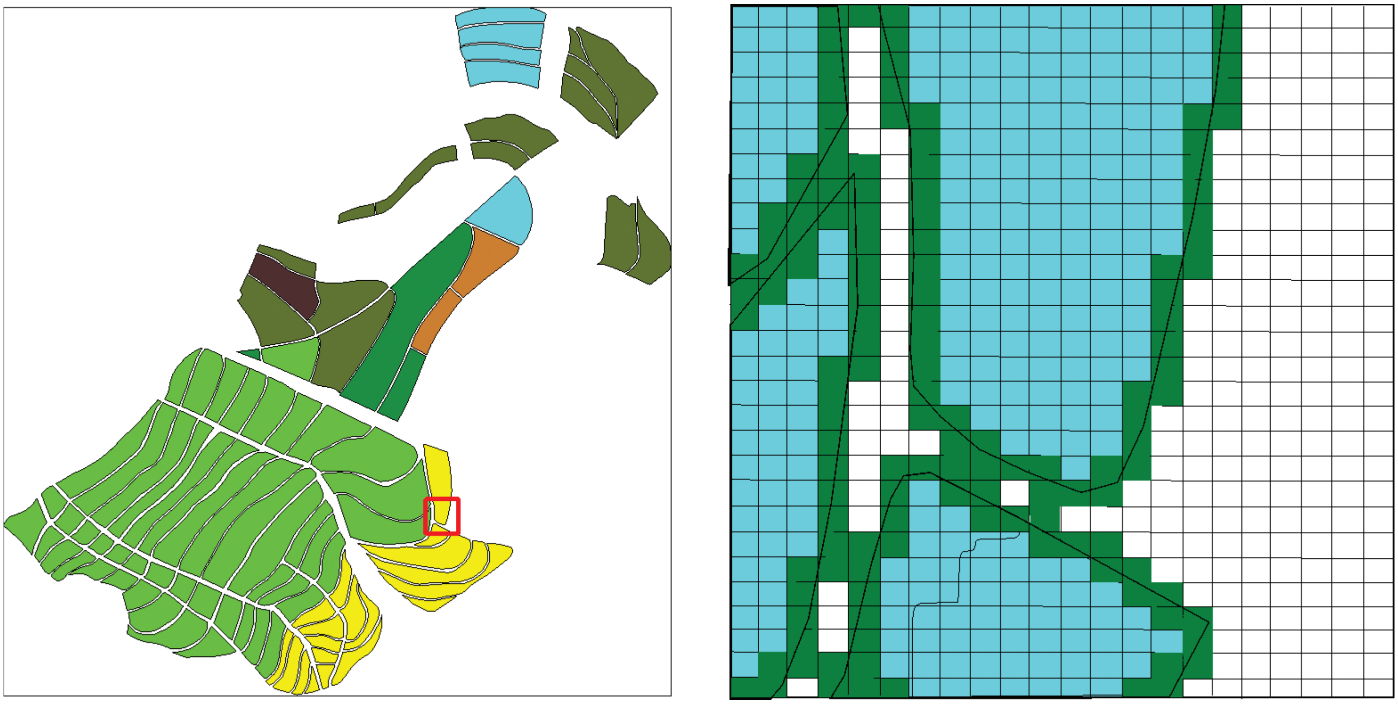

Fig. 5. The discretization of the spatial domain. On the left a typical sugarcane field layout is illustrated with different colors representing crop age, and on the right the discretized domain corresponding to the area within the red square. This was done by transforming the spatial information obtained from the shapefiles to a matrix data structure in Matlab containing the entries '0', '1' and '2' denoting non-sugarcane patches, patches inside a field and edge patches, respectively. In the right half of the figure these data are represented by white, blue and green, respectively.

entries '0', '1' and '2' to distinguish between patches inside a field, edge patches and non-sugarcane patches, respectively. The following assumptions were made: (1) zero-flux Neumann boundary conditions are assumed; no dispersal of moths across the boundary is therefore allowed, (2) the paths separating the fields from each other are either considered as part of the neighboring sugarcane fields, or in areas where the paths are too wide, are considered to be boundaries across which no dispersal of moths may occur between fields at these points, (3) an edge patch is defined as a patch that contains the boundary line of a certain field (see Fig. 5). A section of each edge patch may contain non-sugarcane areas (for example a section of a separating path)—these areas are assumed to contain sugarcane, and therefore are part of the nearest field. The total area of the implemented domain is therefore slightly larger than the actual size of the domain. If an edge patch is shared between 2 different fields, the patch is assigned to only 1 of the fields, (4) the different fields in the domain are assumed to be heterogeneous in terms of crop age and variety, in accordance with the information contained in the GIS shapefiles, (5) boundary conditions as specified by Potgieter et al. (2013) are assumed, with boundaries occurring along the edges of fields nearest to the surrounding non-sugarcane areas.

The graphical user interface also provides a means of simulating rectangular domains containing fields of different sizes, ages and varieties, and arranged according to specified patterns. The patterns implemented include fields distributed in lanes and in a checkerboard formation, as described by Potgieter et al. (2015).

Secondly, the algorithm described below was implemented to simulate an *E. saccharina* infestation scenario on the implemented sugarcane domain. The algorithm combines calculations from the 4 different subsystems described in the previous section, performed for a specified domain, and calculates the final estimated IS profit, infestation level and crop damage index. The input required includes the discretization of the specified domain (as obtained from the first algorithm), the layout of the sugarcane fields contained in the domain together with information on their initial crop ages, crop resistance ratings, field perimeters and field areas. The initial stalk length and density-dependent mortality rate at the start of the simulation are then calculated accordingly. All *E. saccharina* growth, maturation, mortality and dispersal parameters are also required, as well as the parameters specific to the IS technique as described by Potgieter et al. (2012, 2013). Insect releases by means of aircraft or all-terrain vehicles (ATVs) driven alongside the edges of sugarcane fields may be simulated in the domain, with releases performed daily, twice a wk, weekly or once every 2 wk. The following assumptions were made: (1) dispersal is assumed to occur only from edge patch to edge patch between 2 fields. *E. saccharina* is considered a weak flier, with a small portion of moths having been recorded to disperse up to 200 m during their lifespan, which is equivalent to an average of between 30 and 40 m per day (Carnegie 1974). Longer range dispersals across fragmented landscapes are therefore not explicitly considered, (2) once a field is harvested, the releases of the irradiated insects commence again after the crop reaches a certain minimum age, (3) the released moths are assumed to spread uniformly along the edge patches of each field (or grouping of fields) where the IS technique is applied, with the edge patches of older fields requiring larger numbers of released moths than newly planted fields, (4) the paths surrounding the sugarcane fields should all be visited at least once during each release session. The distance travelled on the release site is approximated by the sum total of the perimeters of the fields (or groupings of fields) where releases occur. A better approximation may, however, be obtained by defining the distance travelled as a Chinese postman problem (CPP) (Edmonds 1965) and employing suitable CPP algorithms to solve for the shortest possible circuit. The release workers may, however, not necessarily travel along an optimal shortest route.

INITIALIZATION

At the start of the algorithm, the initial *E. saccharina* infestation on the domain is determined. The initial infestation levels of newly planted or harvested fields are assumed to be between 0 and 1 *E. saccharina* larva and pupa/100 sugarcane stalks (e/100 stalks). For older sugarcane fields, the initial infestation levels are estimated by utilizing the mean-field model of Potgieter et al. (2012). Initial values of fertile egg, larval, pupal and moth population densities are computed according to the relations described by Potgieter et al. (2013).

THE MAIN LOOP

The algorithm first performs calculations assuming no releases of irradiated insects, after which the release ratio η (as specified in the input), is used in calculations. During each time step, the temperature τ is sampled for the specific d. The mortality and maturation rates are then determined accordingly. The stalk length bored at temperature τ is also determined using the reciprocal of the maturation rate multiplied by 42.525, the average length of feeding required per larvae (Keeping & Govender 2002; Potgieter et al. 2012).

The algorithm then continues by determining the set of positions in the discretized domain that are considered candidate sugarcane patches for the releases. In order to be a candidate site for the IS, the crop age at a position must fall within a minimum and maximum crop age range specified as input. Also, depending on the release method, the IS is only applied along the predetermined release lanes in the domain. After the candidate positions have been determined, the release rate at each position is determined according to the chosen release ratio, and the infestation level at the start of the releases. The cost of the releases is also calculated in a manner similar to the method explained by Potgieter et al. (2012).

The algorithm then loops through all positions in the discretized domain and calculates the crop damage index, the density-dependent mortality, the probabilities of mating, and the fertilization probabilities. The dispersal rate (diffusion term) and population growth (reaction term) at each position is also determined. The population size for the next time step is then calculated, as well as the stalk length and crop age.

Before continuing to the next time step, all the positions in the discretized domain that are ready for harvesting, are determined. For all positions at which sugarcane may be harvested, the final sucrose value at harvest time is calculated, along with the estimated revenue. The stalk length, crop age and crop damage index are reset to zero, and the *E. saccharina* infestation level is reset to an initial infestation level assumed at age zero.

TERMINATION

After the last time step, the total cost associated with the IS technique is calculated for all positions, as well as the total revenue estimated for the entire domain. The percentage profit of using the IS technique is determined after the algorithm has looped through both a scenario without the IS technique and a scenario with the IS technique. The percentage profit of using the IS technique, *E. saccharina* infestation level and percentage damage are returned as output.

THE GRAPHICAL USER INTERFACE

Upon execution of the simulation tool, the graphical user interface, shown in the screenshot in Fig. 6, appears. For each scenario, a simulation start time and an end time should be chosen. The output produced at the end of the simulation will be valid for the chosen period. The simulation start time and the simulation end time input fields contain 2 drop-down menus each, one indicating the mo, and the other indicating the year at which the simulation is started. The graphical user interface also contains 2 panels, each with specific input fields that have to be populated by the user in order to finally run a simulation and obtain output for a specific scenario. Once the user has specified input values in all the input fields, the simulation may be started by clicking on the start button in the top right corner (see Fig. 6). When the simulation starts, a progress bar indicates how far the simulation is from completion. A number of output graphs are available for further analysis at the end of the simulation. These include a 2-dimensional graphical representation of infestation and damage across the domain at the end of the simulation period, the average infestation and damage as a function of time, the average infestation, damage as well as revenue per ha per field at harvest time.

Results

A pilot site near Eston, KwaZulu-Natal (29.912289S; 30.647178E) was chosen to illustrate the simulation tool described in the previous sections. This site was chosen in view of its isolation and the fact that it is surrounded by other land uses, which correspond to the model assumptions made (a closed domain with zero-flux Neumann boundary conditions). The site comprised a total of 45 ha of sugarcane varieties N12, N37, N31, N44, N45 and N50, all of which were considered to be moderately resistant varieties against *E. saccharina*. The sugarcane field layout was heterogeneous in terms of crop age, with a sugarcane growth cycle of 24 mo. The initial crop ages contained in the shapefiles representing the pilot site were rounded to the nearest mo. An *E. saccharina* infestation of 0.1 borers/100 stalks was assumed uniformly distributed within each field. No fields were therefore excluded from infestation. Releases of irradiated insects by means of ATVs driven alongside the edges of the sugarcane fields were simulated, with releases performed once a week. At a release ratio of 40:1 in each respective field, releases of irradiated insects resulted in a suppressed average *E. saccharina* infestation of below 5 e/100 stalks (i.e., number of borers per 100 stalks) over the domain (see Fig. 7). Closer examination of the results revealed that, although the average infestation across the domain was suppressed, the average infestation levels in some individual fields were still high due to release lanes being too far apart (see Figs. 8 and 9). Our recommendations, given the above release strategy, are to adjust the field layout (not a likely outcome), or to consider ground releases inside the fields instead of only around the edges, or to consider the more costly approach of aerial releases.

Discussion

A high-level design of a simulation tool for investigating different IPM strategies against a number of pest species in sugarcane was presented in this paper. The system consists of 4 interacting subsystems, namely the pest species population dynamics, the sugarcane dynamics, the environmental dynamics and the economics subsystem. For the purposes of research on *E. saccharina* in relation to the IS technique, the simulation tool currently includes only *E. saccharina* population dynamics under the influence of the IS technique. The tool may be extended to include other pest species population dynamics, along with their corresponding pest control measures, such as biological control and habitat management, as part of a decision support system for IPM. In this paper, a description was given of an IS simulation tool developed by incorporating the mean-field and spatio-temporal models of Potgieter et al. (2012, 2013). In addition, an example simulation output of a pilot site was also given for illustrative purposes. Using the simulation tool, it is possible to test the outcome of different release strategies without having to conduct expensive in-field experiments. Although

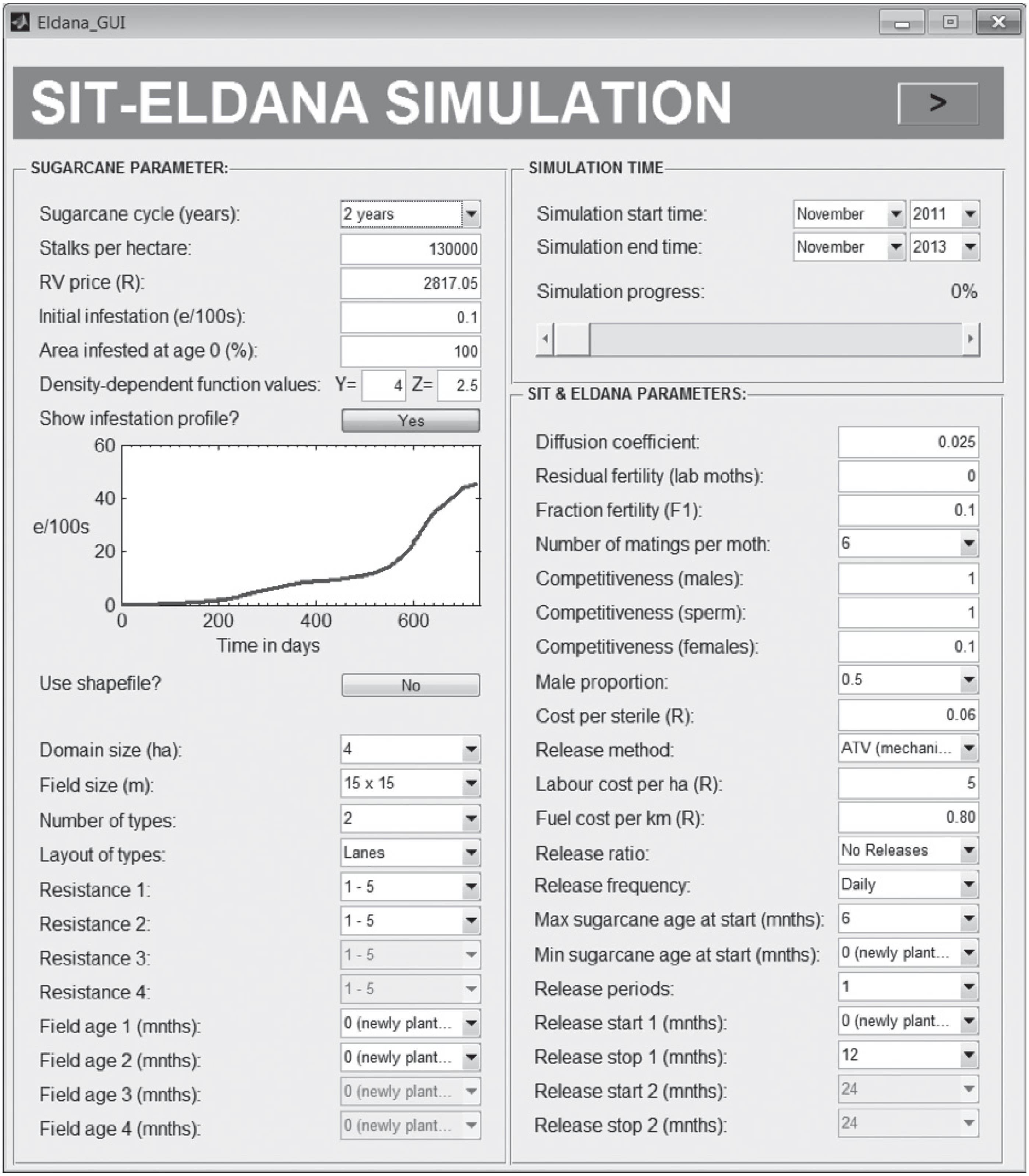

Fig. 6. The graphical user interface designed for the SIT/IS simulation tool for the field application of a SIT/IS strategy against *Eldana saccharina* in sugarcane. The initial infestation, e/100s, is the number of borers per 100 stalks of sugarcane.

the mean-field and spatio-temporal models currently employed by the simulation tool work well within a context of the IS technique, using the models to include other additional IPM strategies may prove difficult. An agent-based simulation model of *E. saccharina* is therefore currently being developed (Van Vuuren et al. 2014) with which a combination of different pest control methods imposed on an *E. saccharina* population may be simulated more accurately. Similar models may also be developed for other important pest species in sugarcane and inte-

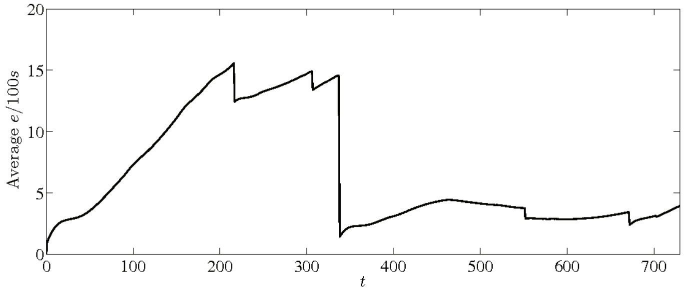

Fig. 7. The average *Eldana saccharina* larval infestation with the passage of time simulated for the SIT/IS pilot site near the Eston area of KwaZulu-Natal, South Africa with weekly releases commencing only in fields of age at most 6 mo at the start of the release. Time, t, is measured in days. The density, e/100s, is the number of borers, e, per 100 stalks of sugarcane. The graph shows that the average infestation level in the second yr of the control program is substantially reduced.

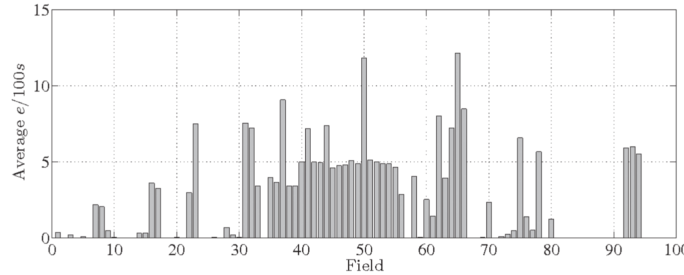

Fig. 8. The average *Eldana saccharina* larval infestation per field at the end of a 24 mo simulated SIT/IS program at the pilot site near the Eston area of KwaZulu-Natal, South Africa. The average number of borers per 100 stalks of sugarcane remains at damaging levels in roughly 10% of the fields subjected to the SIT/IS program.

Fig. 9. A spatial overview of the *Eldana saccharina* larval infestation at the end of a 24 mo simulation of a SIT/IS program at the pilot site near the Eston area of KwaZulu-Natal, South Africa. The colors indicate infestation levels measured in e/100 stalks, i.e., number of borers per 100 stalks of sugarcane. The fields colored in dark blue in the top right corner are aged 0, 1 and 2 mo, and they were harvested just before the end of the simulation; therefore the infestation levels are still low and this is before the commencement of releases of irradiated adult moths.

grated in the pest species subsystem. Other possible improvements to the simulation tool include the inclusion of a more complicated and realistic sugarcane growth model, as well as the inclusion of environmental factors in addition to temperature.

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References Cited

Barclay HJ. 1980. The sterile release method on species with two-stage life cycles. Researches on Population Ecology 21: 165-180.

Barclay HJ. 1982. The sterile release method with unequal male competitive ability. Ecological Modelling 15: 251-263.

Barclay HJ. 2001. Modelling incomplete sterility in a sterile release program: Interactions with other factors. Researches on Population Ecology 34: 91-107.

Barclay HJ. 2005. Mathematical models for the use of sterile insects, pp. 148-163 *In* Dyck VA, Hendrichs J, Robinson AS [eds.], Sterile Insect Technique. Principles and Practice in Area-wide Integrated Pest Management. Springer, Dordrecht, The Netherlands.

Barclay HJ, Mackauer M. 1980. The sterile insect release method for pest control: A density-dependent model. Environmental Entomology 9: 810-817.

Barnes BN, Hofmeyer JH, Groenewald S, Conlong DE, Wohlfarter M. 2015. The sterile insect technique in agricultural crops in South Africa: A metamorphosis…but will it fly? African Entomology 23(1): 1-18.

Berryman A. 1967. Mathematical description of the sterile male principle. The Canadian Entomologist 99: 858-865.

Bezuidenhout CN. 2000. A model review and proposed mechanistic tiller model for the CANEGRO sugarcane crop model. MSc thesis, Technikon Natal, Durban, South Africa.

Canegrowers. 2002. The RV cane payment system. Online. Accessed 7-VIII-2015. Available from http://www.sacanegrowers.co.za/facts-figures/rv-cane-payment-system.

Carnegie AJM. 1974. A recrudescence of the borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae). Proceedings of the South African Sugar Technologists Association 48: 107-110.

Conlong DE. 1997. Biological control of *Eldana saccharina* Walker in South African sugarcane: Constraints identified from 15 years of research. Insect Science and its Applications 17(1): 69-78.

Conlong DE. 2001. Biological control of indigenous African stemborers: What do we know? Insect Science and its Applications 21(4): 267-274.

Conlong DE, Rutherford RS. 2009. Conventional and new biological and habitat interventions for integrated pest management systems: Review and case studies using *Eldana saccharina* Walker (Lepidoptera: Pyralidae), pp. 241-261 *In* Peshin R, Dhawan A [eds.], Integrated Pest Management: Innovation-Development Process. Springer, New York.

Edmonds J. 1965. The Chinese postman problem. Operations Research 13(1): 373.

Goebel FR, Way MJ. 2003. Investigation of the impact of *Eldana saccharina* Walker (Lepidoptera: Pyralidae) on sugarcane yield in field trials in Zululand. Proceedings of the South African Sugar Technologists Association 77: 256-265.

Inman-Bamber NG. 1991. A growth model for sugarcane based on a simple carbon balance and the CERES-Maize water balance. South African Journal of Plant and Soil 8(2): 93-99.

Keeping MG, Govender N. 2002. Update on methodology used in screening for resistance to *Eldana saccharina* Walker (Lepidoptera: Pyralidae) in potted sugarcane. Proceedings of the South African Sugar Technologists Association 76: 593-596.

Klassen W, Creech JF. 1971. Suppression of pest populations with sterile male insects. Agricultural Research Service, USDA, Miscellaneous Publication No. 1182.

Manoranjan VS, Van den Driessche P. 1986. On a diffusion model for sterile release. Mathematical Biosciences 79: 199-208.

Miller DR, Weidhaas DE. 1974. Equilibrium populations during a sterile-male release program. Environmental Entomology 3(2): 211-216.

Morgan KT, McCray JM, Rice RW, Gilbert RA, Baucum LE. 2015. Review of current sugarcane fertilizer recommendations: A report from the UF/IFAS Sugarcane Fertilizer Standards Task Force. Soil and Water Science Department, University of Florida, UF/IFAS Extension. Publication SL 295. EDIS. http://edis.ifas.ufl.edu.

Potgieter L, Van Vuuren JH, Conlong DE. 2012. Modelling the effects of the sterile insect technique applied to *Eldana saccharina* Walker in sugarcane. ORiON 28(2): 59-84.

Potgieter L, Van Vuuren JH, Conlong DE. 2013. A reaction-diffusion model for the control of *Eldana saccharina* Walker in sugarcane using the sterile insect technique. Ecological Modelling 250: 319-328.

Potgieter L, Van Vuuren JH, Conlong DE. 2015. The role of heterogeneous agricultural landscapes in the suppression of pest species following random walk dispersal patterns. Ecological Modelling 306: 240-246.

Prout T. 1978. The joint effects of the release of sterile males and immigration of fertilized females on a density regulated population. Theoretical Population Biology 13: 40-71.

Rutherford RS. 2015. An Integrated Pest Management (IPM) Approach for the Control of the Stalk Borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae). The South African Sugarcane Research Institute; ISBN: 1-874903-41-7

South African Sugar Association. 2015. Industry overview. Accessed 7-VIII-2015. Available from http://www.sasa.org.za .

The Mathworks Inc. 2013. Mapping Toolbox version 3.7. Computer Software. Natick, Massachusetts.

Van Vuuren BJ, Potgieter L, Van Vuuren JH. 2014. Prerequisites for the design of an agent-based model for simulating the population dynamics of *Eldana saccharina* Walker. Proceedings of the 2014 Operations Research Society of South Africa (ORSSA) Annual Conference 62-70.

Webster TM, Maher GW, Conlong DE. 2005. An integrated pest management system for *Eldana saccharina* in the midlands north region of KwaZulu-Natal. Proceedings of the South African Sugar Technologists Association 79: 347-358.