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Antone dos Santos Benedito

Thesis presented to São Paulo State University (UNESP) for the degree of Doctor of Biometry.

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São Paulo - Brazil
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Adviser: **Cláudia Pio Ferreira**
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ATA DA DEFESA PÚBLICA DA TESE DE DOUTORADO DE ANTONE DOS SANTOS BENEDITO, DISCENTE DO PROGRAMA DE PÓS-GRADUAÇÃO EM BIOMETRIA, DO INSTITUTO DE BIOCIÊNCIAS - CÂMPUS DE BOTUCATU.

Aos 21 dias do mês de fevereiro do ano de 2020, às 14:00 horas, no(a) LDI III do Departamento de Bioestatística, Biologia Vegetal, Parasitologia e Zoologia, reuniu-se a Comissão Examinadora da Defesa Pública, composta pelos seguintes membros: Profa. Dra. CLAUDIA PIO FERREIRA - Orientador(a) do(a) Departamento de Bioestatística, Biologia Vegetal, Parasitologia e Zoologia / Instituto de Biociências de Botucatu - UNESP, Prof. Dr. RENATO MENDES COUTINHO do(a) Centro de Matemática, Computação e Cognição / Universidade Federal do ABC - UFABC, Prof. Dr. WESLEY AUGUSTO CONDE GODOY do(a) Departamento de Entomologia e Acarologia / ESALQ - USP - Piracicaba/SP, Prof. Dr. JOSÉ BRUNO MALAQUIAS do(a) Departamento de Bioestatística, Biologia Vegetal, Parasitologia e Zoologia / Instituto de Biociências de Botucatu - UNESP, Prof. Dr. PAULO FERNANDO DE ARRUDA MANCERA do(a) Departamento de Bioestatística, Biologia Vegetal, Parasitologia e Zoologia / Instituto de Biociências de Botucatu - UNESP, sob a presidência do primeiro, a fim de proceder a arguição pública da TESE DE DOUTORADO de ANTONE DOS SANTOS BENEDITO, intitulada **MULTI-STAGE POPULATION MODELS APPLIED TO INSECT DYNAMICS**. Após a exposição, o discente foi arguido oralmente pelos membros da Comissão Examinadora, tendo recebido o conceito final: aprovado. Nada mais havendo, foi lavrada a presente ata, que após lida e aprovada, foi assinada pelos membros da Comissão Examinadora.

Profa. Dra. CLAUDIA PIO FERREIRA Claudia Pio Ferreira

Prof. Dr. RENATO MENDES COUTINHO

Prof. Dr. WESLEY AUGUSTO CONDE GODOY

Prof. Dr. JOSÉ BRUNO MALAQUIAS José Bruno Malaquias

Prof. Dr. PAULO FERNANDO DE ARRUDA MANCERA

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Abstract

This thesis presents two manuscripts previously sent to publication in scientific journals. In the first manuscript, a delay differential equation model is developed to study the dynamics of two *Aedes aegypti* mosquito populations: infected by the intracellular bacteria *Wolbachia* and non-infected (wild) individuals. All the steady states of the system are determined, namely extinction of both populations, extinction of the infected population and persistence of the non-infected one, and coexistence. Their local stability is analyzed, including Hopf bifurcation, which promotes periodic solutions around the nontrivial equilibrium points. Finally, one investigates the global asymptotic stability of the trivial solution. In the second manuscript, after rearing soybean looper *Chrysodeixis includens* in laboratory conditions, thermal requirements for this insect-pest are estimated, from linear and nonlinear regression models, as well as the intrinsic growth rate. This parameter depends on the life-history traits and can provide a measure of population viability of the species.

Contents

1 INTRODUCTION

Insect invasions and insect outbreaks have dominated the headlines worldwide for decades. Some of them are important agents of large economic losses and of disease transmission. Numerous efforts have been employed by the scientific and no-scientific community to treat these issues by solving or softening them. Applied mathematics and statistics, often combined, are an relevant support to this purpose, since they allow to understand, describe and evaluate the underlying mechanisms of insect dynamics. Tools like differential equations (deterministics and stochastics), optimization models, regression models, survival analysis, individual-based models, complex networks and many others have been broadly used.

Abiotic factors such as temperature and humidity, influence insects temporal and spatial dynamics both directly and indirectly. The direct influence can be observed through limiting and stimulating the activity of larvae and adults, insect dispersal, insect development rate, insect survival in adverse weather conditions, etc. Indirect influence includes modulation of the environment where the insect lives, such as plant formation and phenology, food quality, number of predators and parasitoids, and activity of entomopathogens (Jaworski & Hilszczański, 2013).

Complex relations among these factors have been gradually understood but not completely explained. For instance, the closer is the environment temperature to the thermal optima, the faster is the insect metabolism leading to greater feeding and mating activities, and the longer is the time seeking places of oviposition. This may increase the chances of dispersing, the frequency of laying eggs, and the probability of colonising a larger number of host plants (Moore & Allard, 2008). The shortening of immature development in higher environment temperatures can result in reproductive success of many insects since there would be a shorter time of immature exposition to adverse conditions such as low temperature, extremely high or inadequate humidity, predator or parasitoid attacks and entomopathogenic activity. Furthermore, fast-growing may, in addition to shorten the biological life cycle, increase the generation number and outbreak frequency of some species (Netherer & Schopf, 2010).

Therefore, understanding the connection between vital rates and temperature variation is crucial for predicting seasonal fluctuation of insect populations and developing strategies of control. Several empirical linear and nonlinear models of temperature-dependent development rate have been established to estimate the vital thermal requirements from life table data of poikilothermic species obtained at constant temperatures in laboratory (Damos & Savopoulou-Soultani, 2012).

Moreover, developmental and other life-cycle traits models might be incorporated in mathematical models to predict seasonal insect abundance and outbreak timing in field. Among them, delay differential equation (DDE) models have shown to be appropriate to describe the dynamics of species with stage-structured life cycles, and they also allow changing the stage duration driven by biotic or abiotic factors.

Besides their exclusive property of capturing delayed feedback, DDE models are only slightly more complex than ordinary differential equation (ODE) to simulate numerically and simpler as for mathematical analysis compared to partial differential equation (PDE) models (Kim et al., 2009). DDE modeling has been used in many distinct areas such as medicine, engineering and industry, ecology, genetics and so on for the most variable applications, e.g. cardiovascular system (Ottesen, 1997), teleoperation problems (Kruszewski et al., 2014), gene regulatory networks (Ahsen et al., 2014), glucose-insulin systems for diabetes patients (Palumbo et al., 2014), neural networks (Orosz, 2014), cell population dynamics in cancer treatment (Avila et al., 2014) among others.

In this context, the current thesis presents two manuscripts already submitted to scientific journals related to both aforementioned classes of biological problem. Two different insects were chosen: (i) *Aedes aegypti* and (ii) *Chrysodeixis includens*. The first one is a known vector of many vector-borne diseases, such as dengue, Zika, Chikungunya, and yellow fever, causing millions of human deaths every year; and the second one is the main plusine pest in the Americas, for the sake of damage caused to soybean and also to many other crop species across a broad geographical range.

The first manuscript introduces a new DDE model, reducible to a Nicholson-type delay system under some parametric conditions, to study the colonization and persistence of *Wolbachia*-transinfected *Aedes aegypti* into environments wherein an uninfected wild mosquito population is already settled. This model is derived by the method of characteristics from a previous PDE model. A broad theoretical analysis is held including positiveness, boundedness, and uniqueness of solutions, local stability of steady states, Hopf bifurcation and the global stability of the trivial steady state given by the extinction of both populations. The results gathered in this work can lead to further study about the influence of abiotic factors on the dynamics of these populations, so long as they cause change in the immature development time, e.g. the temperature.

In the second manuscript, the thermal requirements of soybean looper *Chrysodeixis includens*, namely lower and upper temperature thresholds and optimal temperature for immature stages, are unprecedentedly obtained through linear and nonlinear temperature-driven models fitted to laboratory data. The latter were also used to evaluate the population viability under different temperatures, for which the intrinsic growth rate was calculated as a function of the life-history traits. Hopefully, the results achieved here may be used to forecast accurately the occurrence of the different stages of *C. includens* in field and help optimize the efforts of controlling this insect-pest. In this sense, a new study addressing the modeling of *C. includens* life cycle by DDE equations considering the temperature-dependence of the model parameters is in progress. This survey will put together the knowledge acquired in the two previous works.

I would like to highlight two periods of my doctorate: (i) supported by CAPES (PDSE process number: 88881.188834/2018-01), a sandwich period from late August 2018 to early March 2019 was done at Inria (Institut National de Recherche en Informatique et en Automatique), Lyon, France. My supervisor abroad was Mostafa Adimy, whose teaching and guidance were important in consolidating the theoretical knowledge about DDE systems; (ii) laboratorial data of *C. includens* were collected from June 2018 to late August 2018 at School of Agricultural and Veterinary Sciences, São Paulo State University (UNESP), Jaboticabal-SP, Brazil, supervised by Odair Aparecido Fernandes. Records of development time, longevity, mortality and fecundity at different temperatures, so far missing in the literature for this species, were performed. This laboratory work has been a wealth of experience in terms of learning and professional formation.

4 CONCLUSIONS AND FURTHER WORK

Two manuscripts already sent to scientific journals are presented in this thesis, opening the way to future work and investigation. The first manuscript enabled me to acquire a robust theoretical learning in mathematical analysis as well as a considerable expertise in computational tools of DDE systems; in turn, the second manuscript permitted me to have a significant background in entomological laboratory, life table data and the use of regression models.

In summary, the first manuscript presents an analytical and numerical analysis about invasion of an *Wolbachia*-infected mosquito population in an area already populated with uninfected mosquitoes. The importance of this study is related to the fact that the infection mediates antiviral protection against a broad range of viruses. The proposed model takes into account several aspects of mosquito life cycle (immature and adult survival, development and oviposition rates) as well as specific features of *Wolbachia* infection on mosquito population (maternal inheritance of bacteria, cytoplasmatic incompatibility, distortion of progeny sex ratio). Differently from other mathematical models already published, our proposition can be easily adapted to consider the influence of abiotic factors on mosquito dynamics. This is important because *Wolbachia* infections in *Ae. aegypti* are vulnerable to high temperatures; heat stress reduces bacteria density in adults and decreases the probability of cytoplasmic incompatibility and maternal transmission. As it is a new model, it is important to discuss the positiveness and boundedness of solutions, as well as the regions of existence and stability of the equilibrium states. We showed that when the delay crosses some thresholds the populations go to extinction. Moreover, its increase can promote, through Hopf bifurcation, stability switch towards instability for the nonzero equilibria. The overview drawn here, can be used as a safe beginning to input more complex mechanisms on mosquito-bacteria-temperature interaction.

The second manuscript explores the use of statistical and mathematical models to address the relation among temperature and mosquito entomological parameters. The novelty relies on the construction of this relationship for the insect-pest *Chrysodeixis includens*. From this work, we can affirm that the overall cycle of this species is feasible between 19.4 to 29.8 degrees Celsius. Therefore, this species viability is restricted to regions where the annual temperature average is in this range. Furthermore, the optimum temperature value for intrinsic growth rate (25.2 degrees Celsius) is consistent with population outbreaks observed in Brazilian soybean. The results obtained here can be used to forecast accurately the occurrence of different stages of *Chrysodeixis includens* in field and help optimize the control of this insect.

Finally, the knowledge and skills developed throughout my doctorate study are undoubtedly meaningful to carry out interdisciplinary collaboration, in particular with researches from entomology that deal with real data and phenological and/or mathematical models. As an example, the knowledge acquired during the development of the two works described before has been used in the construction of a DDE system to model different stages of *Chrysodeixis includens* life cycle where all parameters depend on temperature. Birth, mortality and developmental models, with fitted parameters coming from the second manuscript, are coupled to this DDE model, whose theoretical background was learned through the first manuscript, in order to get realistic seasonal fluctuations of the populations. Afterwards, control functions simulating insecticide application will be added to the model dynamics. This work is currently underway.

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