University of São Paulo
“Luiz de Queiroz” College of Agriculture

Dynamics and pest and natural enemies dispersion in cowpea and colored cotton in sole or intercropping systems

Francisco Sales Fernandes

Thesis presented to obtain the degree of Doctor in Science. Area: Entomology

Piracicaba
2018

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Undergraduate in Agrarian Sciences

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
Prof. Dr. **WESLEY AUGUSTO CONDE GODOY**

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1. Modelos matemáticos e estatísticos 2. Simulações computacionais 3. Pulgões e predadores 4. Perfil de aminoácidos I. Título

DEDICATION

This thesis is dedicated to my father Antonio Fernandes da Silva "*in memorian*" and all my family that has been fundamental in my life.

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EPIGRAPH

«L'Eternel est mon berger:

Je ne manquerai de rien».

Psaumes 23:1

CONTENTS

RESUMO

Dinâmica e dispersão de pragas e inimigos naturais em feijão-macassar e algodão colorido nos sistemas de cultivo solteiros e consorciados

Consórcios são importantes práticas culturais comumente utilizadas no manejo de pragas. Baseiam-se no princípio de que a redução de populações de insetos-praga nos cultivos pode ocorrer devido ao aumento na diversidade do agroecossistema. O estudo foi conduzido objetivando avaliar o impacto que o consórcio entre algodão com fibra colorida e o caupi pode causar nas populações dos pulgões *Aphis gossypii* Glover, 1877, *Aphis craccivora* Koch, 1854 (Hemiptera: Aphididae) e seus predadores, especialmente *Cycloneda sanguinea* (Linnaeus, 1763) (Coleoptera: Coccinellidae). Objetivou-se também avaliar a produção de biomassa e comportamentos de dispersão dos pulgões e seus inimigos naturais nos cultivos. Experimentos foram conduzidos em condições laboratoriais, casa de vegetação e campo. Realizaram-se extrações de aminoácidos oriundos de plantas de algodão e feijão. Em casa de vegetação, ápteros de duas espécies de pulgões (*A. gossypii* e *A. craccivora*) e um predador (*C. sanguinea*) foram utilizados para avaliar a dispersão, preferência pelo hospedeiro bem como o estabelecimento da progênie do predador. A influência de fatores abióticos (temperatura e umidade relativa) na dinâmica dos pulgões também foi analisada. Em condições de campo, avaliou-se a ocorrência de artrópodes encontrados no algodoeiro e caupi solteiros e consorciados. Modelos matemáticos foram desenvolvidos para avaliar a dinâmica de pulgões ao longo do tempo e modelos estatísticos foram utilizados para comparar produtividade em plantas, dispersão, progênie e sucesso reprodutivo do predador. Simulações computacionais foram utilizadas para comparar a ocorrência de insetos e avaliar o melhor sistema de consórcio que reduza a população de pragas, aumentando a população de inimigos naturais e produtividade do cultivo. O aminoácido asparagina (ASP) foi predominante na maioria das amostras. Correlações positivas foram encontradas entre pulgões e temperatura. Correlações negativas foram encontradas entre pulgões e umidade relativa. Modelos matemáticos descreveram o comportamento dinâmico dos pulgões nos arranjos estudados. Em todos os esquemas de cultivos foi observado um crescimento assintótico, com picos populacionais e decréscimos na população dos pulgões. Em casa de vegetação, os cultivos solteiros propiciaram números de pulgões maiores do que os arranjos de cultivos consorciados. A dispersão do inimigo natural foi similar nos sistemas de cultivos solteiros e consorciados. Entretanto, a abundancia de sua progênie e produtividade de algodão foi maior no tratamento t_1 (Consórcio delineado com plantas de algodão : plantas de feijão, cada linha iniciou e terminou com plantas de algodão). Simulações baseadas nos experimentos em condições de campo e literatura demonstram que alguns sistemas de cultivos propiciaram dinâmica temporal estável nos artrópodes estudados. Porém, *Toxomerus watsoni* (Curran, 1930) (Diptera: Syrphidae) apresentou dinâmica temporal instável e menor abundância nos arranjos de algodão solteiro orgânico ou no consórcio de algodão e feijão t_1, que recebeu inseticida para controle das pragas sugadoras. Simulações computacionais confirmaram que a produção de biomassa foi maior em alguns consórcios de algodão com caupi do que em cultivos solteiros.

Palavras-chave: *Aphis craccivora*; *Aphis gossypii*; Predadores; Consórcio; Pragas agrícolas

ABSTRACT

Dynamics and pest and natural enemies dispersion in cowpea and colored cotton in sole or intercropping systems

Intercropping is an important cultural practice commonly used in pest management. It is based on the principle that the reduction of insect pest populations in the crop may occur due to the increase of agro-ecosystem diversity. The study was carried out aiming to assess the impact of colored fiber cotton-cowpea intercropping on both *Aphis gossypii* Glover, 1877 and *Aphis craccivora* Koch, 1854 (Hemiptera: Aphididae) aphid populations and their predators, especially *Cycloneda sanguinea* (Linnaeus, 1763) (Coleoptera: Coccinellidae). The study also aimed to evaluate the biomass production and the dispersion behavior of the aphids and their predators in this context. Experiments were carried out in laboratory, greenhouse and field conditions. Amino acids were extracted from cotton and cowpea plants. Under greenhouse conditions two wingless aphid species (*A. gossypii* and *A. craccivora*) and one predator species (*C. sanguinea*) were used to evaluate the dispersion, crop preference as well as predator progeny establishment. The influence of abiotic factors (temperature and relative humidity) in aphid dynamics was also analyzed. In field conditions the occurrence of arthropods found in sole or cotton and cowpea intercropped was evaluated. Mathematical models were developed to evaluate the aphid dynamics over time and statistical models were used to compare productivity in plants, dispersion, progeny and reproductive success of predator. Computational simulations were performed to compare the insect occurrence and to evaluate the best cropping system to pest reduction, natural enemy increase and plant productivity. Amino acid asparagine (ASP) was the most detected in the samples. Positive correlations were found between aphids and temperature. Negative correlations were found between aphids and relative humidity. Mathematical models described the dynamics behavior of aphids in arrangements studied. In all cropping systems an asymptotic growth was observed, with population peak and decrease in aphid population. Under greenhouse conditions, the sole cropping exhibited higher number of aphids than intercropping systems. The natural enemy dispersion was similar in both cropping system. However, the progeny abundance and cotton productivity were higher in treatment t_1 (intercropping designed with cotton plants : cowpea plants in a row, started and ended with cotton plants). Simulations based in field experiments and literature showed that some cropping arrangements provided temporal dynamics stable in arthropods. However, *Toxomerus watsoni* (Curran, 1930) (Diptera: Syrphidae) exhibited temporal dynamics unstable and less abundance in arrangements of sole organic cotton or cotton-cowpea intercropping t_1 that received insecticide for sucking pest control. Computational simulations confirmed that biomass production was higher in some cotton-cowpea intercropped than in sole cropping systems.

Keywords: *Aphis craccivora*; *Aphis gossypii*; Predators; Intercropping systems; Agricultural pest

1. INTRODUCTION

The cowpea (*Vigna unguiculata* Linnaeus Walp.) is a vegetable cultivated in tropical and subtropical regions, being an important food source (Adati et al. 2008; Oyewale & Bamaiyi 2013; Tiroesele, Thomas, & Seketeme 2015). Its utilization has different functions (Oyewale & Bamaiyi 2013), such as green source, soil nitrogen fixation (Konlan, Abudulai, & Birteeb 2016), etc. It is also a protein supplement (Carvalho et al. 2017), being considered a very important food source to the Brazilian population (Frota, Soares, & Arêas 2008). Cotton crops (*Gossypium hirsutum* L. r. *latifolium* Hutch) have been a fundamental cash crop to countries such as India, China, United States, Pakistan and Brazil (USDA 2018). Various cotton fibers made worldwide are white (Carvalho et al. 2014). In Brazil the cotton with white fibers was planted in large quantity in many states, but with the introduction of some insect pests in different places (Cavalcanti 2012), nowadays, this kind of crop is principally planted in Bahia and Mato Grosso (USDA 2018). Therefore, trying to invigorate the agribusiness of cotton in our country, many cotton cultivars with colored colors have been developed (Cavalcanti 2012; Carvalho et al. 2014). This was possible because the heritage of coloration is relatively simple and the heritability characteristics are high to make some change in the fiber color (Carvalho et al. 2014). Among the cotton with colored fibers, the BRS Safira is one of the most important cultivars developed to aggregate value to the farms of rural producers, reducing costs with water and colorants in the industrial process to obtain the final product. The genetic characteristic was obtained crossing herbaceous cotton from United States of America (brown-colored cotton) with CNPA 87-33 cultivar (cotton with white fiber) from Brazil, that provides tender leaves to the cultivar which could affect negatively the sucking insect in agroecosystems (Ramalho et al. 2012b).

Arthropods occurrence is expressive in both cotton and cowpea plants. Their abundance can be dangerous or beneficial to the plants. Abundance is dangerous since it can reduce photosynthetic activity in leaves and transmit virus to plants (Baloch et al. 2016). In cotton, the species considered pest can reduce the quality of the plant, open boll and seed production (Ramalho 1994). *Bemisia tabaci* biotype B (Gennadius, 1889) (Hemiptera: Aleyrodidae), and aphids are the most important pests that can cause loss production in these crops. The species *Aphis gossypii* Glover, 1877 (Hemiptera: Aphididae) is a polyphagous pest, frequently found in all cotton crops systems, as well as in many plant families worldwide (Wrona et al. 1996; Luo et al. 2016; Wang et al. 2016). The critical period of occurrence of this species in cotton plants can take place early (few days after plant sprouting), and the

estimated loss vary from 24 to 44% (sole crops), with 71% of infested plants (Ramalho 1994). *Aphis craccivora* Koch, 1854 (Hemiptera: Aphididae) is considered one of the most abundant insects in Leguminosae plants (Kamphuis, Gao & Singh 2012; Wongsa et al. 2016) since it can reduce the quality of the host plant (Meradsi & Laamari 2016). Although there is no information about the critical period for the occurrence of *A. craccivora* in cowpea (BRS Itaim cultivar) in Brazil, the production loss caused by this species and other phytophagous insects in sole crops is evident, and it can vary from 24 to 69% (Karungi et al. 2000). It is also known that for *B. tabaci* the critical feeding period is closely related with the attainment of any critical weight of insects and the pest can be most abundant in the field when there are climatic conditions favorable for its activity (Gelman & Hu 2007; Kataria et al. 2017).

Both cotton and cowpea can also be fundamental for the attractiveness to natural enemies (Manjula & Lakshmi 2014). Coccinellidae family (Manjula & Lakshmi 2014; Ali et al. 2016; Vinod et al. 2016), predator Aracnidae, parasitoids (Prasad & Malathi 2016; Ali et al. 2016), Neuroptera (*Chrysoperla* sp.), Diptera, as well as *Allograpta* sp. (Colmenárez et al. 2016) are among the most frequent arthropods found in these plants. The arthropods previously mentioned are important due to their generalist predatory activity, which can act in different agroecosystems. However, one of the factors affecting pests and populations of natural enemies is non-selective pesticide utilization, which can reduce both populations of pest and natural enemies (Ahmad et al. 2016). The evolution of natural agroecosystems is controlled by high biodiversity levels (Malézieux et al. 2009). Landscape simplification often reduces the natural control of pests by the action of natural enemies (Rusch et al. 2016) since it does not contribute with the reproduction and multiplication of beneficial arthropods in the agroecosystem. There is experimental evidence showing that intercropping systems of cotton-cowpea may contribute to the reduction of non-selective pesticide use, contributing to the decrease in the population of aphids and the increase in the diversity of natural enemies (Ramalho et al. 2012a; Fernandes et al. 2015). However, information from this nature is incipient, especially taking into account any expected effect of cotton with colored fiber and cowpea on natural enemies.

As in intercropping systems, two or more crops can be planted in the same area (Tung et al. 2016), maintaining the biodiversity of floral and feeding resources for natural enemies, thus contributing to the reduction of pest population in cotton (Fernandes et al. 2012; Rao et al. 2012), causing impact on insect dynamics in intercropping systems (Altieri & Letourneau 1982). Several studies have shown that agroecosystem diversification can reduce pest infestation (Jankowska & Wojciechowicz-Żytko 2016). The understanding of diversity plant

effect on herbivorous control is relevant for the understanding of agricultural sustainability (Dassou & Tixier 2016). It is believed that the ecological model of cotton-cowpea intercropping systems include an essential step in the development of algorithms as a scenario with intercropping, sucking insect, as well as natural enemies.

Mathematical and statistical models may be used to describe biological dynamics systems, with dependent sensitivity of mathematical functions inserted in algebraic equations (Bolker 2007). Analytical tools can be used to describe and interpret dynamics including predator and prey, by incorporating different variety and sensitive parameters to measure the action of insects in crops (Ogal et al. 2016). On the other hand, the knowledge of biological patterns, quality and quantity of practice used by rural producers, and the evaluation of the relationship between intercropping systems and impacts on agricultural systems over time and space is recommended to make some models applicable to agroecosystems (Silvie et al. 2010).

The research was carried out with the general aim to assess the impact of colored fiber cotton-cowpea intercropping on both *A. gossypii*, *A. craccivora* aphid populations, their predators, especially *Cycloneda sanguinea* (Linnaeus, 1763) (Coleoptera: Coccinellidae), as well as their dispersion behavior and biomass production. It was hypothesized that a) cotton intercropped with cowpea reduces *A. gossypii* population in cotton crop, and b) cotton intercropped with cowpea increases *C. sanguinea* ladybug population in cotton crop.

1.1. Polyphenism in aphids

Polyphenism is the occurrence of phenotype within a species whose development is affected by environmental conditions (Chapman 1969). In agroecosystem, a single genotype can produce distinct phenotypes (Braendle et al. 2005). In various insect groups, the species exhibit a type that affects the flight of individuals (Harrison 1980). Commonly, the development of wing by individual can be different according to population size, resource competition, nutritional condition of plant, geographical area, environmental change, food quality, predators, photoperiod, temperature, reduction of ecdysone signaling, or seasonality of species (Müller, Williams & Hardie 2001; Niva & Tekeda 2003; Brisson 2010; Vellichirammal et al. 2017). Many aphid species in Brazil reproduce by parthenogenesis. Parthenogenetic aphids are viviparous, in which individuals are developed in female ovarioles before the eclosion of nymphs. The adults of aphids can be winged or wingless, which depends on the influence of many factors as mentioned previously (Brisson 2010; Ogawa & Miura 2014). In general, aphid mothers that perceive a crowded habitat transmit the

information to the daughter embryos, and then the progeny tends to be winged (Müller, Williams & Hardie 2001; Brisson 2010). On the other hand, if the habitat has sufficient food resource, the wingless individuals can reproduce and their progeny can also be wingless (Dixon 1998). In the present study, polyphenism was indirectly studied by the measurement of the effect of temperature, relative humidity, and amino acids profile on the number of wingless and winged aphid within different cropping arrangement. The knowledge of these factors is essential for the development of a model that explains the population growth of aphids within cotton and cowpea in sole or intercropping systems over time.

1.2. Biological and cultural pest control

Biological control is the utilization of individuals (natural enemies) for pest control. On the other hand, cultural control is the utilization of agronomics practices and multiple cropping to reduce insect population and increase the population of natural enemies in agroecosystem (Mahr & Dittl 1986; Parra 2014; Oaya et al. 2017). The natural enemies usually used in agriculture are predators, parasitoids and pathogenic agents (Parra et al. 2002). Although the biological control of insects by predator is an important practice used in many countries worldwide, its use is still limited in Brazil (Parra 2014). Intercropping design in any cultural practice is commonly found in this country, but it has been used only in small production scale by family agriculture or experimentation in Northeast region (Ramalho et al. 2012b; Fernandes et al. 2015). Both cultural and biological control can be optimal elements for the development of any analytical tool useful to evaluate the effect of cropping diversification on pest-beneficial insect dynamics over time, allowing the prediction of demographics process within, between, and among arthropods population dynamics (Lima, Pereira & Godoy 2009; Hatt et al. 2018; Xia et al. 2018).

1.3. Radiation and biomass production

Radiation is an essential component to crop growth, insect communication by visual cues, and biomass production (Kropff & Laar 1993; Gallo et al. 2002; Chimonyo, Modi & Mabhaudhi 2016a). In field condition, the radiation use efficiency of plants changes over the day, and also according to nitrogen and water limitation, cropping systems association, shading intensity, and geographic locations due to differences in environmental or constitutive parameters of each plant as secondary metabolites, temperature, accumulation of photosynthetic pigments, and vapor pressure deficit (Gonias, Oosterhuis & Bibi et al. 2012;

Chakwizira et al. 2018; Alam et al. 2018). The utilization of optimal intercropping system provides increase in land productivity, and consequently in plant biomass since it improve soil nutrients, water use and solar radiation, which are necessary for the crop growth during its vegetative and reproductive development (Tsubo, Walker & Mukhala 2001; Zhang et al. 2007; Umesh, Chittapur & Jagadeesha 2017). Radiation and intercropping systems also enhance plant defense against pests (Dillon et al. 2017). Population of aphids can be slowly affected by the incidence of ultra violet radiation since they are very dependent on this kind of radiation to host selection in the agroecosystem (Dáder et al. 2017; El-Aal, Rizk & Mousa 2018). Infra-red radiation is another component that can affect the communication in some groups of insects in the landscape (Gallo et al. 2002). In this sense, this type of information is essential so that the ecologist can choose the best cropping system and predict real plant productivity as well as insect communication providing implementation of integrated pest management in the field.

1.4. Review of the main models found in literature and their applications

This topic was written with the objective to show the models used to evaluate the plants of sole cotton, sole cowpea, intercropping systems, as well as the pest and natural enemies' dynamics, aiming at the development of various models in order to explain the scenario in Brazil. In mathematical modeling there are crucial steps to be observed by modelers, which can be viewed in Figure 1.

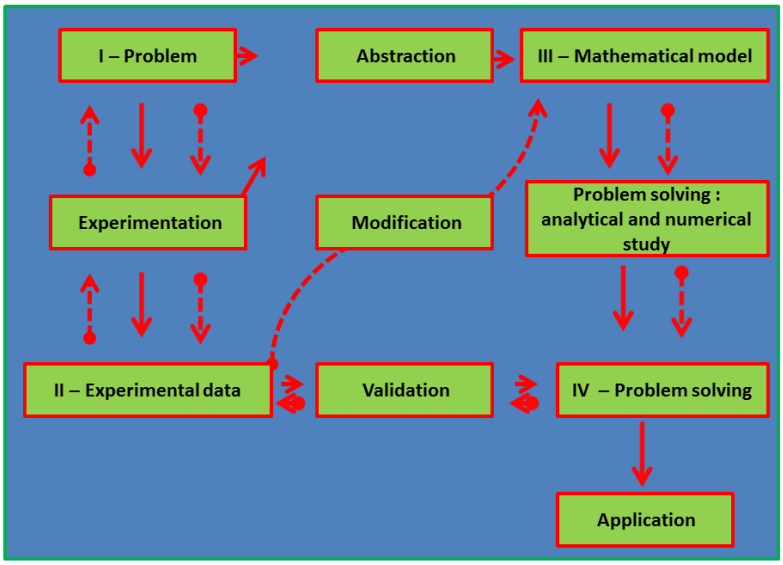

Figure 1. Step necessary to construct a model. Modified from Bassanezi (2013)

In table 1, a summary of statistical and mathematical models used to study sole crops, intercropping systems and insects' dynamics around the world is shown. These models are

interesting as basis for the development of our proposition allowing us to explain the relationships within and among various scenarios.

Table 1. Summary of the main models found in literature and their applications

Model	Cotton	Cowpea	Intercropping	Pest	Natural enemy	References
GOSSYM	Yes					Thorp et al. 2014
Cotton2K	Yes					Thorp et al. 2014
COTCO2	Yes					Thorp et al. 2014
OZCOT	Yes					Thorp et al. 2014
CROPGRO	Yes	Yes				Thorp et al. 2014
EPIC	Yes	Yes				Thorp et al. 2014
WOFOST	Yes					Thorp et al. 2014
SUCROS	Yes					Zhang et al. 2008; Thorp et al. 2014
GRAMI	Yes					Thorp et al. 2014
GD	Yes					Antonini et al. 2011
CROPSYST	Yes		Yes			Thorp et al. 2014
AquaCrop	Yes					Thorp et al. 2014
APSIM	Yes		Yes			Gaydon et al. 2017
FSPM – CottonXL	Yes					Gu et al. 2014
COTON	Yes					Jallas et al. 1999
AMAPpara	Yes					Reffye et al. 1999
DSSAT CSM-CROPGRO	Yes					Loison et al. 2017
Hanks (H-2)		Yes				Adekalu & Okunade 2008
Stewart (S-2)		Yes				Adekalu & Okunade 2008
Butcher (H-B)		Yes				Adekalu & Okunade 2008
NIR		Yes				Ishikawa et al. 2017
PRECIS		Yes				Cavalcante Júnior et al. 2016
STICS			Yes			Brisson et al. 2004; Kollas et al. 2015
DAISY			Yes			Kollas et al. 2015
FASSET			Yes			Kollas et al. 2015
HERMES			Yes			Kollas et al. 2015
MONICA			Yes			Kollas et al. 2015
LIN-TUL			Yes			Kollas et al. 2015
SODCOM			Yes			O'Callaghan, Maende & Wyseure 1994
NextGen			Yes			Antle et al. 2017
Differential equations	Yes	Yes	Yes	Yes	Yes	Matis et al. 2005; Patil & Mytri 2013; Wang, Cao, Huang 2013
APHISim				Yes		Piyaratne et al. 2014
GPDM				Yes		Kyogoku & Sota 2017
Lyapunov				Yes		Ngalya & Kuznetsov 2017
LaSalle's				Yes		Ngalya & Kuznetsov 2017
CLIMEX					Yes	Poutsma et al. 2008
Holling					Yes	Papanikolaou et al. 2016
Crowley-Martin					Yes	Papanikolaou et al. 2016
Beddington-DeAngelis					Yes	Papanikolaou et al. 2016
Hassell-Varley					Yes	Papanikolaou et al. 2016
Lotka and Voltera					Yes	Hadžiabdić, Mehuljić & Bektešević 2017
MPP					Yes	Rafikov & Balthazar 2005
DP					Yes	Rafikov & Balthazar 2005
GMM-based				Yes		Wang, Cao, Huang 2013
KPM-based				Yes		Wang, Cao, Huang 2013
Fuzzy model				Yes	Yes	Peixoto, Bassnezi & Fernandes 2015
SEM					Yes	Alyokhin et al. 2011
AMOS					Yes	Alyokhin et al. 2011

Which: GOSSYM = Simulator of Cotton Crop Growth and Yield, EPIC = Environmental Policy Integrated Climate, WOFOST = World Food Studies, SUCROS = Simple and Universal Crop Growth

Simulator, CropSyst = Cropping Systems Simulation Model, AquaCrop = Water Driven, APSIM = Agricultural Production Systems Simulator, FSPM = Functional Structural Plant Model, AMAPpara = Programme Modélisation des Plantes, DSSAT = Decision Support System for Agrotechnology, NIR = Transfer; Near Infrared Spectroscopy, PRECIS = Providing Regional Climates for Impact Studies, NextGen = Next-generation crop models, CSMs = Crop Simulation Models, STICS = Simulateur Multidisciplinaire pour les Cultures Standard, IDEs = Integro-Differential Equations, GPDM = Absolute Density Dependence, SEM = Structural Equation Modeling, AMOS = Adequate Estimation of Model Coefficients, MPP = Maximum Principle of Pontryagin, DP = Dynamic Programming, GD = degree-days, FASSET = Farm Assessment Tool, SODCOM = A Solar Driven Computational Model of Crop Growth, GMM = Gaussian Mixture Model, KPM = Kernel Polynomial Method and SEM = Structural Equation Modeling

1.4.1. Cotton models

History of cotton simulation models, applications, opportunities for improvement, use in scientific research, and decision support were revised (Thorp et al. 2014). It was observed that SUCROS-cotton model can be useful to evaluate cotton productivity taking into account many factors as the range in temperature, incoming radiation, crop management practices, types of cultivars for different agroecological conditions, and resource-use efficient cropping systems (Zhang et al. 2008). Empirical statistical models were interesting to study different agrosystems since they allowed the analysis of fuel wood needs during dry and wet season as well as the constancy of food grain need (Youl et al. 2008). Some models provided theoretical insights that can contribute to the improvement of water use efficiency in cotton cultivation and the identification of optimal application rates of soil conditions necessary for the development and productivity of plants (Su, Wang & Shan 2015). A mathematical model was developed and validated to estimate the duration of cotton cycle in the State of Goiás, Brazil (Antonini et al. 2011). It was found that the models performed very well when they were compared with statistical models. In a study with APSIM, it was found that the model simulated the cropping system performance very well in Asia, and it can be applied in many types of crops, varieties and environments as well as in various management practices around the world (Gaydon et al. 2017).

FSPM model was useful to evaluate the effects of agronomic practices in the study of cotton plant structure (Gu et al. 2014). GOSSYM model was interesting to study climatic-cotton interactions (Liang et al. 2012). COTONS model was used to provide predictions at a more regional level, which could then be coupled with databases for soil, climate, etc. (Jallas et al. 1999). AMAPpara model evaluated plant growth and for this, the authors took into account its physiological functioning and its architectural development (Reffye et al. 1999). DSSAT, CSM-CROPGRO-cotton were used to identify the best cultivars for Northern Cameroon (Loison et al. 2017). It was found that: 1) cultivars which grow in the predicted

area will be unsuitable in the future; 2) there is an optimized cultivar for each criterion tested, but none to optimize more than one satisfactorily, and 3) optimized cultivars are interesting in the systems because they can increase photosynthetic rate, and consequently, productivity (Loison et al. 2017). All revised models to sole cotton showed that their application can be interesting to analyze loss due to distinct abiotic factors over time.

1.4.2. Cowpea models

To analyze cowpea, other models were developed in order to observe different aspects of the cropping systems. Hanks (H-2), Stewart (S-2) and the Butcher (H-B) models that evaluate the performance of crop water efficiency were used by Adekalu & Okunade (2008) who found that H-2 was the most water-efficient model, since it provides greater yield for cowpea during the growth stage. It was concluded that the CROPGRO-cowpea model is useful to simulate the growth and development of cowpea in Brazil (Lima Filho, Coelho Filho, & Heinemann 2013a). It was also important to analyze the existence of limitations to seeding the crop under water deficit conditions in Recôncavo in Bahia State, and to evaluate the sensitivity for the climatic variations in plants intra year (Lima Filho, Coelho Filho, & Heinemann 2013a; Lima Filho, Coelho Filho, & Heinemann 2013b).

EPIC models were useful in simulation of K dynamic in the soil under regional scale (Barros, Williams & Gaiser 2004). On the other hand, Imaging Model Analysis Program used to perform NIR, showed that it was also possible to analyze grain quality as well as the amount of nitrogen present in the seeds of cowpea genotypes (Ishikawa et al. 2017). PRECIS model predicted that climate changes had no direct influence on some cowpea cultivars, but evapotranspiration could be reduced in approximately 5%, temperature could be increased over the limit tolerated by the crop, causing negative effects in its development (Cavalcante Júnior et al. 2016). As revised to cotton, the models studied here showed that the applications can be similar to estimate plant biomass, allowing the evaluation of the loss in productivity caused by abiotic factors.

1.4.3. The intercropping systems models

Intercropping models generally have considerable variation in complexity and functionality, ranging from a dynamic global vegetation model to agroecosystem models designed for field-scale application. In general, crop simulation models should be applied to the analysis of many cropping combinations in order to evaluate systems diversity accurately

(Chimonyo, Modi & Mabhaudhi 2015). The following models: DAISY, FASSET, HERMES, MONICA, STICS, LIN-TUL and CROPSYST, have been applied to study rotation and single crops (Kollas et al. 2015). The results obtained using SODCOM model indicated that intercropping systems improve productivity in locations where the land has little resources (O'Callaghan, Maende & Wyseure 1994). Estimates using geometrical radiation transmission model demonstrated that it is possible to evaluate spatial and temporal variability of radiation in strip intercropping systems, whose finding may be helpful for modeling plant growth dynamics in many intercropping systems (Wang et al. 2017). Next-generation crop models explained the response of complex cropping systems under different sustainable intensification management strategies (Antle, Jones & Rosenzweig 2017).

Both APSIM crop models at field level as APSIM model to simulate systems design at regional level can predict productivity and stability of intercropping systems under conditions with abiotic constraints (Li-li et al. 2015). It was also observed that APSIM model can be used to make some simulations allowing the evaluation of intercropping systems under different water regimes, as well as changes in plant phenology, biomass, yield, best management practices, and crop water use over time (Chimonyo, Modi & Mabhaudhi 2016a; Chimonyo, Modi & Mabhaudhi 2016b). Simulations with STICS model showed that it is possible to analyze many combinations of crops as arable crops, forage and perennial crops. It could also be a useful tool to predict many other agronomic strategies as intercropping systems that can be applied in the farm (Brisson et al. 2004). The models revised for intercropping systems were also important because they can be useful to compare different factors that can affect loss in the productivity of the plant over time.

1.4.4. Pest models

Several models have been developed to study pest dynamics in sole crops or intercropping systems (Matis et al. 2005; Patil & Mytri 2013; Tonnang et al. 2017). Integro-differential equations (IDEs) and mechanistic models can be used as a powerful tool since they performed the insect dynamics in the same proportion as the classical nonlinear regression (Wang, Cao & Huang 2013). Stochastic population size model showed that it is possible to use differential equations to predict the peak aphid count and final cumulative count, helping ecologists understand the size of the peak and its implications to pest management. On the other hand, the stochastic model can be useful to estimate the variability in the peak of aphid when cumulative counts are studied (Matis et al. 2005). Intelligent systems for effectual prediction of pest population dynamics of sucking insects on cotton were

important since it allowed the comparison of the fluctuation of pest over weeks in different crops, being the model applied to evaluate *Thrips tabaci* in cotton and the best to explain its dynamics (Patil & Mytri 2013).

The results of a computer program based on Factor Analysis integrated into APHISim model suggest that overall weather effect was more suitable for catastrophe theory applications in population dynamics. It was also observed that it improves a stand along program, including no similar types of study object that could be useful to compare effects on subjected phenomena and weather factors as catastrophe on population dynamics of aphids (Piyaratne et al. 2014). On the other hand, GPDM showed that range in density of pests can affect their reproductive interference (Kyogoku & Sota 2017). A mathematical model to study the impact of *B. tabaci* in dynamics of *Tomato yellow leaf curl virus* predicted that the disease dynamic can range according to basic reproductive number (R_0). If $R_0 = 1$, the dynamics is globally stable, if $R_0 > 1$, the dynamics is globally asymptotically stable and if $R_0 < 1$, the dynamic is unstable (Ngalya & Kuznetsov 2017). The revised models here can be useful to perform a model to evaluate the dynamics of insects in different cropping systems, as well as to predict the loss caused by pest and diseases over time.

1.4.5. The natural enemies' models

To simulate the dynamics, dispersal, behavior and predation rate of ladybirds, distinct models were developed around the world. As temperature-dependent development influences production rates of arthropods (Quinn 2017), CLIMEX model was used to evaluate the distribution of the *Harmonia axyridis* (Poutsma et al. 2008). It was observed that the predator can be found in many places of Mediterranean Europe, South America, Africa, Australia and New Zealand (Poutsma et al. 2008). SEM model was used to analyze the influence of natural enemies and weather on population growth of aphids (Alyokhin et al. 2011). The sample size of population was estimated with the software AMOS. The results explained the coexistence of different aphids' species in the same host plant. On the other hand, the model predicted that weather factors and natural enemies can contribute to the regulation of pest populations. Mathematical simulation models showed that the increase of the invasive alien species can affect the native species; however, aphids and ladybirds dynamics can be closely correlated within their habitat (Kindlmann, Honêk & Martinková 2017).

Houdková & Kindlmann (2006) observed the influence of metapopulation level in population dynamics of aphidophagous predator–aphid system. They considered a fixed number of patches to construct their model. The patches simulated can be applied to a single

shoot, a plant, or a patch, according to the mobility of the individuals considered by the researcher. To construct the model, differential equations considering changes in the cumulative density of prey, changes in prey density as well as reduction in predator density due to cannibalism were used. It was found that, if predators arrive early, they decrease the density of malefic insects in agroecosystem. They can also affect the amplitude and oscillations of pest number over time.

Holling type II, Crowley-Martin, Beddington-de Angelis and Hassell-Varley models were used to evaluate data and compare probabilities of the density of prey only attacked and prey consumed (Papanikolaou et al. 2016). They found that the feeding rates of coccinellid insects are not affected by mutual interference competition when a high number of prey is offered. MPP and DP models used to evaluate the population control problem described by the set of differential equations documented that the optimal pest control problem can be well formulated and resolved using two control functions and pest control accomplishing computational experiments to predict real scenarios with only natural enemies (Rafikov & Balthazar 2005). Prey-predator mathematical model, taking into account diseases, insecticide and two-stage infection in prey population, was used by Nandi et al. (2015), who reported that interactions between some susceptible pest and predator can remain stable for much time of their survival. They also observed the persistence of susceptible pest population for a long period in absence of insecticide in their habitat.

A fuzzy model was used to describe the interaction between *Aphis glycines* and its predator. The model developed included biotic and abiotic factors. It was found that it can be a powerful tool to predict the time and number of predators that could be released in the agroecosystems aiming biological control of aphids (Peixoto, Bassanezi & Fernandes 2013). Lotka-Volterra model with two predators and their prey was used to analyze population dynamics. It was found that the model simulated the dynamics of individuals in different points of equilibrium, in which, some points can be unstable, and others can be non-hyperbolic points, not allowing analysis of their stability (Hadžiabdić, Mehuljić & Bektešević 2017). The models revised in this topic were interesting because they promoted the understanding of different applications as well as the premise to the development of a model that can be applied to explain behavior of populations of natural enemies, and their relationship with the main pest studied within sole cotton, sole cowpea, and intercropping systems.

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2. AMINO ACIDS PROFILE AND IMPACT OF ABIOTIC FACTORS IN APHIDS DYNAMICS IN SOLE COTTON, SOLE COWPEA AND COTTON-COWPEA INTERCROPPING SYSTEMS

Abstract

Aphids can cause direct and indirect damage to cotton and cowpea plants. Some cropping design can contribute with aphid reduction. However, the influence of amino acids and abiotic factors in aphid dynamics in sole or intercropping systems of cotton and cowpea has been little studied. Our aim with this experiment was to study the amino acids profile and the influence of abiotic factors in aphid dynamics in plants of sole crops or cotton-cowpea intercropping systems. Fourth instar nymphs of *Aphis gossypii* Glover, 1877 were released in one plant of sole (t_4) or in one plant of intercropped cotton (t_1 = one row of cotton and one row of cowpea alternate, t_2 = one plant of cowpea and one plant of cotton alternate in the same row and t_3 = one column of cotton and one column of cowpea alternate). Similarly, fourth instar nymphs of *Aphis craccivora* Koch, 1854 were released in one plant of sole (t_5) or in one plant of intercropped cowpea (t_1, t_2 and t_3). The measurement of aphids, temperature (ºC) and relative humidity (%) were recorded at 7, 14, 21, 28, 35, 42 and 49 days after the plants were first infested. Forty - five days after plants sprouted, three apical leaves of sole or intercropping systems of each cotton and cowpea were washed for amino acids extraction. Positive correlations were found when temperature was analyzed in winged *A. gossypii*, wingless *A. craccivora*, and winged *A. craccivora*. On the other hand, negative correlations were found analyzing winged *A. gossypii* and wingless *A. craccivora* concerning relative humidity. Asparagine (ASN) was the most present amino acid in plants of cotton from intercropping systems and sole cropping. The amino acids profile in plants of cowpea was different among treatments. The amino acids found in cowpea intercropping systems t_1 were asparagine (ASN), aspartic acid (ASP), glutamic acid (GLU) and serine (SER). Independently of spatial configuration, the amino acid composition, temperature (ºC) and relative humidity (%) were important factors in winged *A. gossypii* and wingless *A. craccivora* on cotton or cowpea and cotton-cowpea intercropping systems.

Keywords: Cotton; Cowpea; Amino acids; Intercropping; Temperature; Relative humidity

2.1. Introduction

Aphis gossypii Glover, 1877 and *Aphis craccivora* Koch, 1854 (Hemiptera: Aphididae) are considered major agriculture pests (Lv et al. 2016; Wei et al. 2017; Zhang et al. 2017). Both aphid species have similar phases of development: nymphal and adults. In the latter, they can be wingless or become winged. Both wingless and winged individuals can cause severe damage to commercial fields and urban green landscapes (Hu et al. 2017). The damages caused by *A. gossypii* on cotton plants (*Gossypium hirsutum* Linnaeus r. *latifolium* Hutch) during their vegetative and reproductive stages are evident. In the first stage, the leaves become shriveled. In the reproductive stage, especially during fruit opening, fiber quality impairment may take place in addition to leaf shriveling (Almeida 2001). Severe

attacks by *A. gossypii* may also lead to leaf area (58%) and biomass (45%) reduction, as well as to smaller number of vegetative branches and shorter plants, which areacts that harm the crop resulting in economic losses (Sarwar et al. 2014). *A. craccivora* also initially infests seedlings and, as the plant develops, it may also infest flowers and pods (Berberet et al. 2009). The aphids suction causes leaf shriveling and bud deformation (Silva, Carneiro & Quinderé 2005). As time goes by and the aphid population increases, the attacked plants become weak due to the amount of removed sap and injected toxins (Silva, Carneiro & Quinderé 2005). *A. craccivora* is an efficient virus transmitter, including *Cowpea aphid borne mosaic virus* (CABMV) and *Black eye mosaic virus* (BICpMV) (Kitajima et al. 2008). *A. craccivora* causes drastic commercial damages to bean plants (Laamari, Khelfa & d'Acier 2008) by reducing seed quality and production (Obopile 2006). The losses caused by this insect may vary among cultivars and may reach 50% (Berlandier & Sweetingham 2003; Obopile 2006).

The most relevant factors affecting herbivorous population and performance of insects in agricultural ecosystems are probably host chemical defenses, nutritional quality, amino acids profile, temperature, relative humidity, rainfall, and natural enemies (Verdugo, Francis & Ramírez 2016; Cui et al. 2017; Pandey & Koshta 2017). As far as the nutritional point of view is concerned, it is known that in general, plant roots can produce some amino acids as glutamine, glutamate, asparagine and aspartate. These groups of amino acids provide the source of nitrogen for many sucking insects (Knight 2015). Large amounts of nitrogen in the leaf phloem and plasma membrane localization of plants are also essential for plant growth and seed development (Santiago & Tegeder 2016). It is known that aphids are highly specialized insects that feed on the phloem-sap of plants and need amino acids for their development (Febvay et al. 1995; Asrorov et al. 2015). Due to higher amount of amino acids in composition of phloem, some aphid species perform better in developmentally young plants than in mature ones (Karley, Douglas & Parke 2002). On the other hand, temperature-dependent development influences production rates of arthropods (Quinn 2017). Constant temperature has significant effect on the efficacy of some aphids' species (Mohammed & Hatcher 2016). Maximum temperature can hamper arthropods population to an extent of 35%. Relative humidity can contribute about 18% in enhancing some insect occurrence and minimum temperature can affect arthropods incidence in -38% (Sathyan et al. 2017).

Cotton fiber is an important raw material to the textile industries and plays a key role in the national economy (Kaur, Kular & Chandi 2017). This characteristic is fundamental to cotton agroecological utilization. It is known that agroecological service crops can increase the vegetation complexity of agroecosystems leading to a positive impact on natural enemies

of arthropod pest and on weed control (Magagnoli et al. 2017). Intercropping systems provide increase of spatial heterogeneity in habitats by promoting fragmentation of the natural habitat (Liu et al 2017). In Brazil it is used in small farms aiming at the reduction of pest population and increase of plant productivity. However, there is not much previous evidence showing that amino acids profile can be influenced by intercropping systems in way, which is different than in sole crops of cotton or cowpea (*Vigna unguiculata* Linnaeus Walp.). Our aim with this experiment was to study amino acid profile and the influence of abiotic factors in aphid dynamics in plants of sole crops or cotton-cowpea intercropping systems. Results will be presented emphasizing the influence of temperature and relative humidity on *A. craccivora*, *A. gossypii*, and also the profile of amino acids from sole or intercropped plants of cotton (BRS Safira cultivar) and cowpea (BRS Itaim cultivar: upright), respectively.

2.2. Material and Methods

2.2.1. Aphid rearing

Wingless individuals of two species of aphids, *A. gossypii* and *A. craccivora*, were collected from cotton in the field stations at ESALQ (latitude: 22°42’77”S and longitude: 47°37’57”W) and in cowpea from Brazilian Agricultural Research Corporation (EMBRAPA Algodão, latitude: 7°8’25”S and longitude: 35°50’16”W), respectively. Both species were reared in laboratory conditions on their respective host plants: cotton and cowpea. The plants were kept in cages coated with anti-aphid plastic screening at 25 ± 1 °C, 70 ± 10% relative humidity and 12 h photophase (Figure 2). The aphids were monitored on the plants daily and individuals were separated according to their life stage: nymphs and adults. Nymphs of both species of aphids (F2) were maintained on their host plants and used in the greenhouse experiments.

Figure 2. Cages used in aphid rearing. Plants of cotton (A) and plants of cowpea (B)

2.2.2. Assay and experimental design

This study was carried out in a greenhouse placed at the Department of Entomology and Acarology, Luiz de Queiroz Agriculture College, University of São Paulo (ESALQ/USP). Cotton and cowpea were sown in a similar plastic bag that is usually used to sown wood. The substrate named “forth conditioner floreiras” and vermiculite were used in a proportion of 4:1, respectively (Figure 3).

Figure 3. Substrate and plastic bags used under greenhouse experiments

The experimental design was random blocks with three intercropping treatments (t_1, t_2 and t_3) and two mono-cropping treatments (cotton: t_4 and cowpea: t_5) (Figure 4). Rows of plants were spaced 0.40 m from each other within each treatment, plants were spaced 0.20 m within each row, and the distance between each block was 1.00 m.

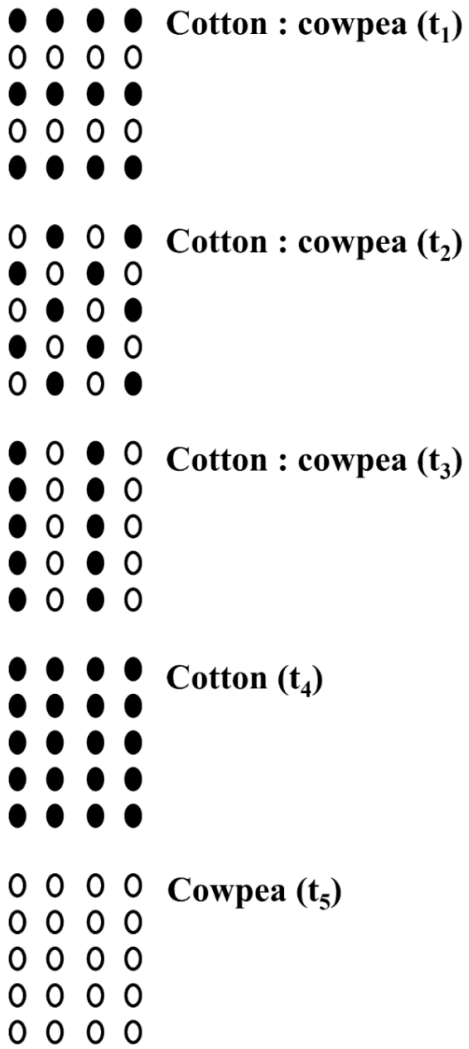

Figure 4. Layout of experiments in cotton–cowpea intercropping systems and monoculture. Cotton with colored fibers (closed circles) and cowpea (open circles)

Twenty-eight days after plants sprouted, 15 fourth instar nymphs of *A. gossypii* and 15 fourth instar nymphs of *A. craccivora* were released in one plant of sole cotton (t_4) and sole cowpea (t_5), respectively (Figure 5). Similarly, one cotton plant and one cowpea plant in each intercropped plot were infested with the aphid species. The number of aphids per plant was recorded weekly between 35 and 77 days after the plants sprouted. The number of aphids was recorded on three plants (previously infested plant and two uninfested plants) in the sole crop

or intercropping systems, which were marked with nylon tape. The counts were made 7, 14, 21, 28, 35, 42 and 49 days after the plants were first infested. Temperature and relative humidity were recorded with a small term-hygrograph placed under greenhouses during experiments.

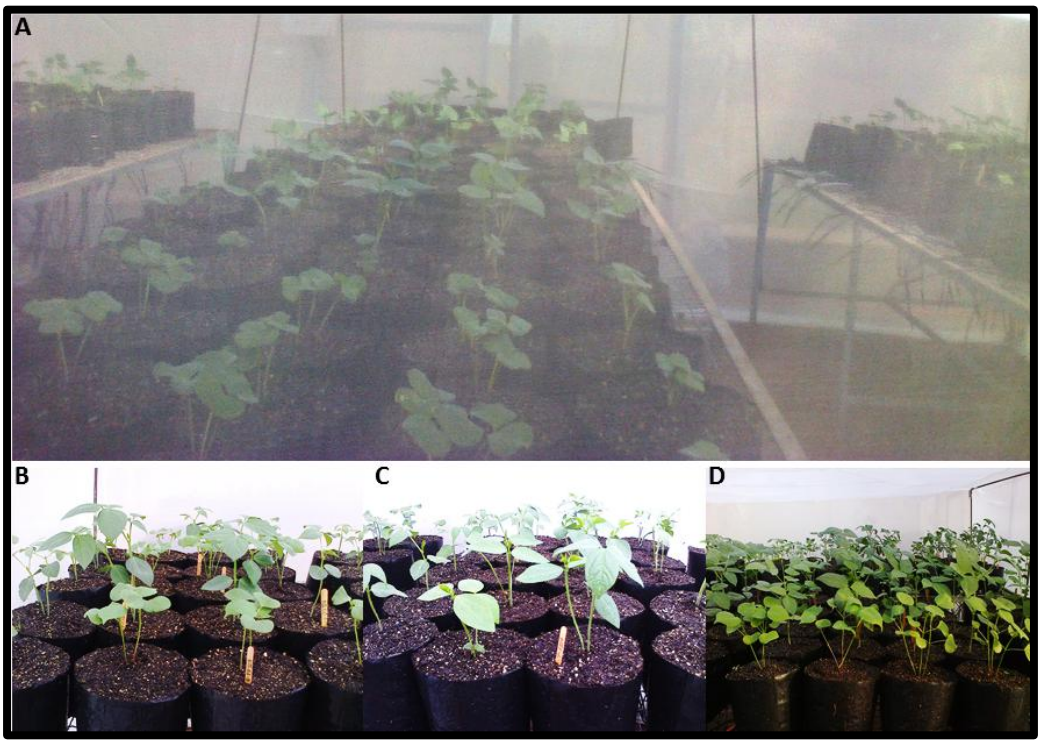

Figure 5. Plants of cotton and cowpea placed in different arrangement in greenhouse experiments. General view: all treatments and blocks inside a big cage in a greenhouse (A), cotton-cowpea intercropping systems t_1 (B), monoculture of cowpea (C) and monoculture of cotton (D)

Forty-five days after plants sprouted (Figure 6), three apical leaves from three plants of sole or intercropping systems of cotton and cowpea were washed with distillated water for amino acids extraction (Weibull, Ronquist & Brishammar 1990; Karley, Douglas & Parker 2002; Aly et al. 2011). Extractions were performed at Laboratório de Fontes Proteicas (FEA) at the University of Campinas (UNICAMP). The extraction duration was 15 minutes shaking and immersing each sample (leaf) in distillated water (10 mL placed in Petri dishes with diameter of 10 cm). Out of 10, only 6 mL of each sample was stored in small *ependorf* tub, refrigerated and sent to FEA at UNICAMP. The samples were lyophilized and high-performance liquid chromatography analysis (HPLC) for free amino acids analyses were done.

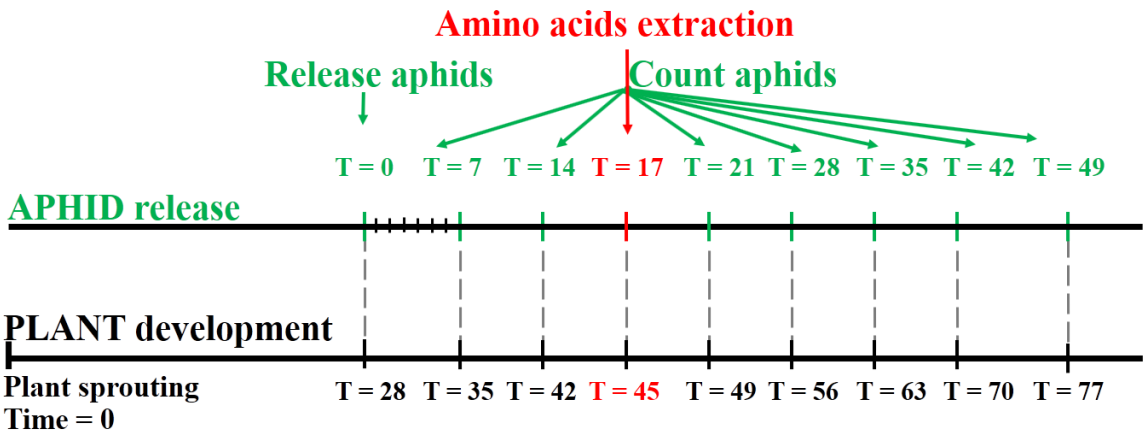

Figure 6. Schematization of days to amino acids extraction

2.2.2.1. Amino acids analyses used in FEA

The method was based in protein hydrolysis with acidified methanol and HCl 0.1M (80% MeOH/20%HCl0.1M) with a proportion of 7:2:1 methanol/internal pattern (White, Hart & Fry 1986). The column used was LUNA 3μ C18 (2) 100 Å 250 X4, 6mm 00G-4251-E0.

The samples were centrifuged, filtrated by molecular exclusion (VIVASPIN 500 MWCO3.000Da), derivatized, homogenized, dried and injected with high-performance liquid chromatography analysis. The results were discriminated in samples from sole cotton, sole cowpea and cotton-cowpea intercropping systems.

2.2.3. Data analysis

The proportion of amino acid found within each treatment was compared by using explanatory analysis. Due to visible non-normal distributions of the data, the number of aphid found, as well as temperature and relative humidity were analyzed by Spearman correlation coefficients (P<0.05). All the analyses were performed using SAS software (https://odamid.oda.sas.com/SASLogon/login?service=https%3A%2F%2Fodamid.oda.sas.com%2FSASStudio%2Fj_spring_cas_security_check).

2.3. Results and discussion

Positive correlations were found between the variables: number of wingless *A. gossypii* and winged *A. gossypii* (ρ = 0.689), wingless *A. gossypii* and winged *A. craccivora* (ρ = 0.717), winged *A. gossypii* and wingless *A. craccivora* (ρ = 0.928), winged *A. gossypii* and winged *A. craccivora* (ρ = 0.933), wingless *A. craccivora* and winged *A. craccivora* (ρ = 0.903). Similarly, positive correlation were also found between winged *A. gossypii* and

maximum temperature (ρ = 0.657), winged *A. gossypii* and mean temperature (ρ = 0.540), wingless *A. craccivora* and maximum temperature (ρ = 0.668), wingless *A. craccivora* and mean temperature (ρ = 0.504), winged *A. craccivora* and maximum temperature (ρ = 0.611), winged *A. craccivora* and mean temperature (ρ = 0.540). On the other hand, negative correlation was found between winged *A. gossypii* and relative humidity (ρ = -0.536), and between wingless *A. craccivora* and relative humidity (ρ = -0.588). This indicates that independently of treatment, there was a period (week) when the increase of maximum temperature and/or decrease of relative humidity contributed to the increase of winged *A. gossypii*, wingless *A. craccivora* and winged *A. craccivora* under greenhouse conditions. It was also observed that over 50% of correlations were significant (Table 2).

Table 2. Correlation between temperature (ºC), relative humidity (%) and aphids found in plants of sole cotton, sole cowpea and cotton-cowpea intercropping systems over time (35 to 77 days after plant sprouting, Figure 6). Piracicaba-SP: 2014

Variable	wingedAg	winglesAc	wingedAc	Tempmax	Tempmin	Tempmean	Rh
winglesAg	0.689*	0.440	0.717*	0.252	0.232	0.325	-0.0951
wingedAg		0.928*	0.933*	0.657*	0.350	0.540*	-0.536*
winglesAc			0.903*	0.668*	0.314	0.504*	-0.588*
wingedAc				0.611*	0.355	0.540*	-0.435*

*Significant Spearman Rank Order Correlation ($P < 0.050$). Scores ≥ 0.70 indicate high correlation between variables, Scores ≤ 0.69 indicate moderate correlation between variables and Scores ≤ 0.29 indicate small correlation between variables. Which: WinglesAg = wingless *Aphis gossypii*, wingedAg = winged *Aphis gossypii*, winglesAc = wingless *Aphis craccivora*, winged *Aphis craccivora*, Tempmax = maximum temperature (24 to 35.5ºC), Tempmin = minimum temperature (21 to 32.3ºC), Tempmean = mean temperature (22.5 to 33.65ºC), and Rh = relative humidity (43 to 93%)

The occurrence of abiotic stresses can alter plant-insect interactions by enhancing host plant susceptibility to other plants or pests (Pandey & Koshta 2017). Demographic parameters as survival, net reproduction rate, number of progeny, generation time and intrinsic rate of increase for *A. craccivora* are strongly affected by fluctuating temperature regimes (Zhaozhi et al. 2016). On the other hand, it is known that biophysical factor of temperature as well as changes in its surfaces (i.e. habitat with low temperature or habitat with high temperature) can affect the biotical potential of aphids (Ramalho et al. 2015). In agricultural systems, effects of temperature on fitness components can facilitate the coexistence of species competing for resources, i.e. if two species belong to the same family and can be fed in the same resource at

the same time but the response to temperature is different between the species, they can be affected by change in temperature and the less adapted species to the habitat can exhibit similar mechanism to the species adapted. Consequently, it can drive difference in their population dynamics (Gao et al. 2016). Independently of cropping systems, this study also documented that maximum temperature and small relative humidity increased winged *A. gossypii*, wingless *A. craccivora* and winged *A. craccivora* numbers under greenhouse conditions. This result corroborates the study carried out by Kataria & Kumar (2015) who explained that aphid population can be significantly and positively correlated with maximum temperature, and negatively correlated with minimum temperature. Similar correlations were also found in a study of aphid population (Ayo-John, Oke & Ishola 2017). However, the results found here disagree with the study carried out by Amin et al. (2017), who commented that the weather can be insignificant on aphid abundance. It is believed that the disagreement between the study carried out by Amin et al. (2017) and the results found in this experiment is probably due the utilization of different cotton variety, which can exhibit distinct plant architecture propitiating small or high relative humidity. The results found in our experiments were essential to understand the correlation of abiotic factors with two aphid species dynamics over time, which is crucial for the development of sustainable pest management (Wang et al. 2015).

Taking into account the cotton cropping systems, it was observed that amino acid profile was similar between sole and intercropping plots (Figure 7). Asparagine (ASN) was the prevalent amino acid in plants of cotton on intercropping systems (t_1: 50%, t_2: 59%, and t_3 58%) and sole cropping (t_4: 54%). Leucine (LEU) and phenylalanine (PHE) were found only in intercropping systems t_2 (Figure 7). On the other hand, the amino acids threonine (THR), ornithine (ORN), proline (PRO), metionine (MET), triptophane (TRP), isoleucine (ILE), valine (VAL) and lysine (LYS) were not found in cotton plants.

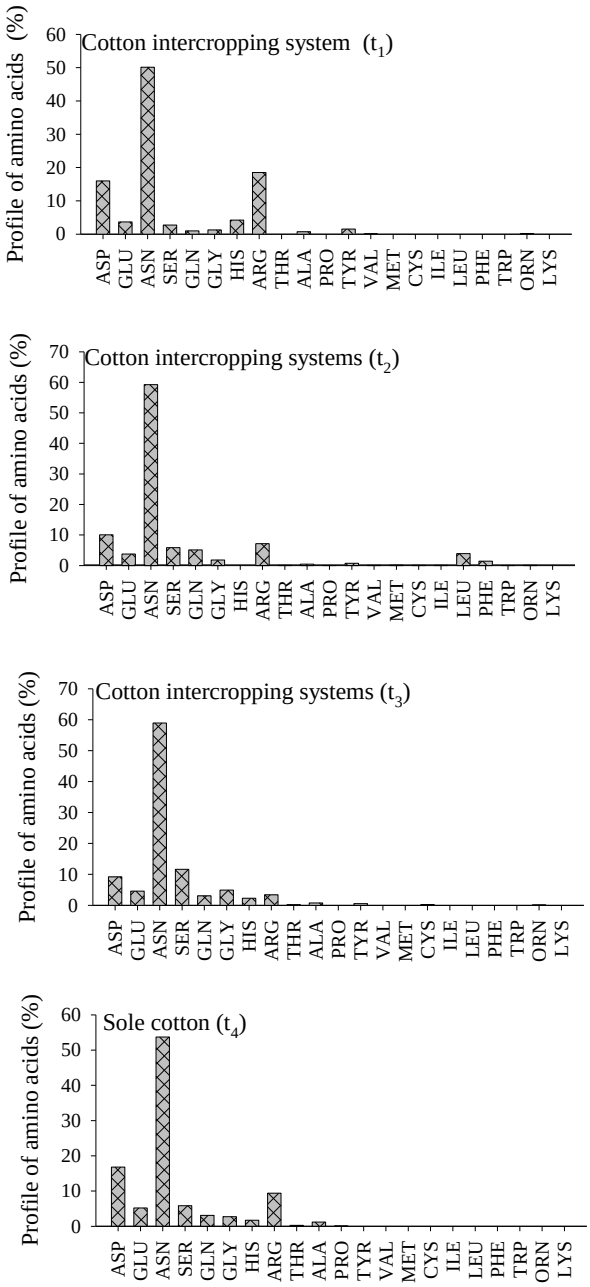

Figure 7. Profile of amino acids from sole or intercropped plants of cotton. Which ASP = aspartic acid, GLU = glutamic acid, ASN = asparagine, SER = serine, GLN = glutamine, GLY = glycine, HIS = histidine, ARG = arginine, THR = threonine, ALA = alanine, PRO = Proline, TYR = tyrosine, VAL = valine, MET = methionine, CYS = cystine, ILE = isoleucine, LEU = leucine, PHE = phenylalanine, TRP = tryptophan, ORN = ornithine and LYS = lysine. Piracicaba-SP: 2014

Observing the free amino acids profile from plants of cowpea (Figure 8), it was found that it can be different among treatments. In cowpea intercropping systems t_1 only the amino acids asparagine (ASN: 21%), aspartic acid (ASP: 30%), glutamic acid (GLU: 20%) and serine (SER: 29%) were the only ones present in extracted samples. In other cowpea designs, asparagine (ASN) was the prevalent amino acid (more than 40%). Leucine (LEU) and

phenylalanine (PHE) were also found in sole cowpea (t_5) and in plants of cowpea in intercropping t_2. Arginine (ARG) was only found in intercropping systems t_2 and t_3 as well as in sole cowpea (t_5), while alanine (ALA) was only found in intercropping systems t_2 and t_3.

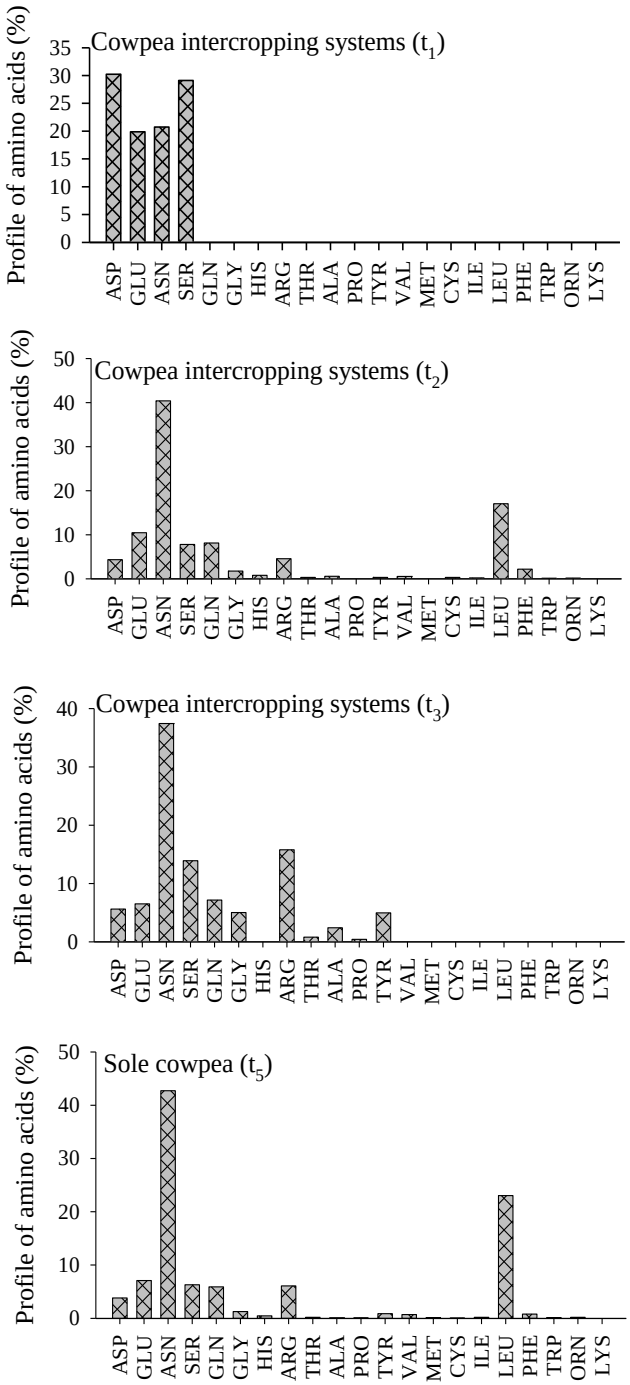

Figure 8. Profile of amino acids from sole or intercropped plants of cowpea. Which ASP = aspartic acid, GLU = glutamic acid, ASN = asparagine, SER = serine, GLN = glutamine, GLY = glycine, HIS = histidine, ARG = arginine, THR = threonine, ALA = alanine, PRO = Proline, TYR = tyrosine, VAL = valine, MET = methionine, CYS = cystine, ILE = isoleucine, LEU = leucine, PHE = phenylalanine, TRP = tryptophan, ORN = ornithine and LYS = lysine. Piracicaba-SP: 2014

Our study showed that asparagine (ASN) was the prevalent amino acid in the samples. This indicates that both cotton and cowpea plants provide essential nutrient for aphid feeding and reproduction during their dispersion over time. Asparagine on plant roots and together with others as glutamine can be converted into essential amino acids, which can provide nitrogen, which is fundamental to aphids feeding (Haribal & Jander 2015). Studies carried out by different researches corroborated the results found in the current investigation, especially when glutamine and asparagine concentrations are compared (Fernandes et al. 2001; Suzuki, Fukushi & Akimoto 2009; Leroy et al. 2011). It was observed that a high amount of glutamine and asparagine was found in *honeydew* of aphids on plants of *Vicia faba* Linnaeus (Leroy et al. 2011). It was also observed that cotton leaf samples can exhibit higher concentrations of alanine, glutamine, proline, lysine and gamma-amino butyric acid (Marur, Sodek & Magalhes 1994).

The results found in this study regarding lysine concentration (Figure 8) were different from results found in other studies (Marur, Sodek & Magalhes 1994), which probably happened due to the utilization of distinct varieties (Fernandes et al. 2001). All results found in literature were interesting to explain the profile of amino acids in sole cropping. However, none of them took into account the effect of intercropping systems and free amino acids profile on aphid dynamics. The results found in this study have positive aspects because they show that distinct intercropping systems of cowpea and cotton, may affect the availability of amino acids required by the aphid species studied. However, amino acid profile from others part, middle and bottom region of the plant, was not evaluated in the current study. This aspect is fundamental, since in same host plant species, amino acids profile can change according to part of plant, plant age and phase of plant (Fernandes et al. 2001). It is suggested that other studies, be carried out taking into account these results found in our experiment.

2.4. Conclusions

The amino acids profile in the leaves of the plants was appropriate to the growth of aphid population within treatments. But that can be different across the experimental design of sole or intercropping systems of cowpea. Relative humidity, mean and maximum temperature were some of the main abiotic factors that caused negative effect on aphid dynamics under greenhouse conditions.

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3. MATHEMATICAL MODELS APPLIED TO POPULATION DYNAMICS OF *Aphis gossypii* GLOVER AND *Aphis craccivora* KOCH (HEMIPTERA: APHIDIDAE): SOLE AND INTERCROPPING SYSTEMS OF COTTON AND COWPEA STUDY[1]

Abstract

Population dynamics of aphids have been studied on sole and intercropping systems. These studies have required the use of more precise analytical tools in order to better understand patterns in quantitative data. Mathematical models are among the most important tools to explain the dynamics of insect populations. This study investigated the population dynamics of aphids *Aphis gossypii* Glover, 1877 and *Aphis craccivora* Koch, 1854 (Hemiptera: Aphididae) over time, using mathematical models composed of a set of differential equations as a helpful analytical tool to understand the population dynamics of aphids in arrangements of cotton and cowpea. The treatments were sole cotton (t_4), sole cowpea (t_5), and three arrangements of cotton intercropped with cowpea (t_1, t_2 and t_3). Mathematical models were used to fit the population dynamics of two aphid species. The model considered that plants were infested with two aphid species and were evaluated at 7, 14, 21, 28, 35, 42, and 49 days after the infestations. There were good fits for aphid dynamics by the mathematical model over time. The highest population peak of both species *A. gossypii* and *A. craccivora* was found in the sole crops, and the lowest population peak was found in crop system t_2 (alternated crops). These results are important for integrated management programs of aphids in cotton and cowpea.

Keywords: Mathematical models; Dispersion; Intercropping systems

3.1. Introduction

The aphids *Aphis gossypii* Glover, 1877 (Ramalho et al. 2012) and *Aphis craccivora* Koch, 1854 (Hemiptera: Aphididae) (Moraes & Ramalho 1980) are serious crop pests in Brazil. These insects directly damage the plants by sucking the phloem sap, and indirectly by virus transmission and excretion of excess carbohydrates from their diet of phloem sap (Bachmann, Nault, & Fleischer 2014). The excretions can foster the occurrence of fungus that inhibits photosynthetic activity, resulting in chlorosis and consequent loss of yield (Bachmann, Nault & Fleischer 2014; Kadam, Kadam & Lekurwale 2014). *A. gossypii* reduced the yield of cottonseed (*Gossypium hirsutum* Linnaeus r. *latifolium* Hutch) by 37% in sole cotton plots compared with 10% loss of cottonseed yield per plant in the intercropping systems (Ramalho et al. 2012b). On the other hand, *A. craccivora* is a vector of several viruses including *Broad bean mosaic virus*, which can reach high abundances in warm-

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temperate and tropical regions (Gutierrez et al. 1974). In comparison with control treatments, biological control of *A. craccivora* with predators increased yields by up to 66% for cowpea *Vigna unguiculata* (Linnaeus) Walp (Munyuli 2009).

Aphid populations can show periodic fluctuations (Brabec et al. 2014). The population dynamics of aphids can be affected by seasonal changes in weather conditions, physiological characteristics of the host plant, farming methods, and management practices (Sequeira & Dixon 1997). Also, some crops may deter while others may attract sucking insects, and local variation in resource quality profoundly influences the overall population dynamics (Kadam, Kadam & Lekurwale 2014; Riolo, Rohani & Hunter 2015).

Although many studies have analyzed the population dynamics of aphid species in sole crops (Sequeira & Dixon 1997; Leite et al. 2007; Rakhshani, Ebadi & Mohammadi 2009), no information is available about the dynamics of *A. gossypii* and *A. craccivora* in different arrangements of cotton intercropped with cowpea. Different crop arrangements or diversification can be effective management strategies to control insect pests (Burgio et al. 2014).

A possible way to represent different feeding preferences among aphids and their ecological relationships is by using mathematical models (Underwood 2009). In this sense, a mathematical model is an equation or a set of equations that represents the behavior of an insect in the system, and gives an approximation of the observed data (Thornley & France 2007). Mathematical models may provide useful and essential analytical tools to interpret important ecological patterns for a given agroecosystem and may also allow predictions to be made about population outbreaks of insect pests. Structured population models are useful to examine population dynamics of insects in crops, and they can be used to explain aphid species competition in situations of limited food resources (Tenhumberg, Tyre & Rebarber 2009; Singh et al. 2014).

Several investigators have developed models to describe population dynamics of aphid species. Plantegenest et al. (1996) used a mathematical approach to simulate changes in populations of the grain aphid *Sitobion avenae* (Fabricius) (Hemiptera: Heteroptera: Aphididae) on wheat, *Triticum aestivum* Linnaeus). Arbab, Kontodimas & Sahragard (2006) tested non-linear and linear models to estimate the development of *Aphis pomi* De Geer (Hemiptera: Aphididae). However, models have not been used to analyze the population dynamics of *A. gossypii* and *A. craccivora* feeding on sole crops or on cotton with naturally colored fiber intercropped with cowpea. Knowledge of distribution patterns of insect pests within intercropping systems is essential to make decisions and implement integrated pest-

management programs in both cotton and cowpea crops. This study investigated the population dynamics of wingless and winged aphids (*A. gossypii* and *A. craccivora*) over time, taking into account different crop arrangements, using mathematical models composed of a set of differential equations as a helpful analytical tool to understand the population dynamics of *A. gossypii* and *A. craccivora* in different arrangements of cotton with cowpea.

3.2. Material and Methods

3.2.1. Mathematical model

The mathematical model used to estimate the population dynamics of wingless and winged aphids in the sole and intercropped plots was comprised of four differential equations, representing the population dynamics of wingless and winged aphids, and cotton and cowpea plants (eqs. 1 - 4). The model considered that plants were infested with two aphid species and were evaluated at 7, 14, 21, 28, 35, 42, and 49 days after the infestations according to assay discussed before (topic 2.2.2).

Equations 1 to 4 describe the population dynamics of aphids (P1 and P2) and plants (P3 and P4). The expected fits were obtained using the equations of the package deSolve library from R software, including:

$$\frac{dP1}{dt} = \alpha 1.P1.P3 + \gamma 1.P1.P4 + \theta 1.P2.P3 + \omega 1.P2.P4 - \lambda 1.P1 \quad (1)$$

$$\frac{dP2}{dt} = \alpha 2.P2.P3 + \gamma 2.P2.P4 + \theta 2.P1.P3 + \omega 2.P1.P4 - \lambda 2.P2 \quad (2)$$

$$\frac{dP3}{dt} = -\beta.P1.P3 - \delta.P2.P3 \quad (3)$$

$$\frac{dP4}{dt} = -\varepsilon.\mathrm{P1.P4} - \varphi.\mathrm{P2.P4} \quad (4)$$

The equation system was solved for each crop system (t_1, t_2, t_3, t_4 and t_5) and species (*A. gossypii* and *A. craccivora*). The model proposed considered that the ecological interaction between aphid species (inter-specific competition) was almost null, and for this reason each species was treated individually.

Each mathematical term is specified in Table 3, and the scheme of the relationships among the variables of the model and parameters are shown in Figure 9.

Table 3. Mathematical terms and their descriptions used to simulation under greenhouse condition. Piracicaba-SP: 2014

Mathematical term	Description
P1	Population of wingless aphids
P2	Population of winged aphids
P3	Population of cotton plants
P4	Population of cowpea plants
α_1.P1.P3	Incoming wingless individuals due to the growth rate of wingless aphids on cotton
α_2.P2.P3	Incoming winged individuals due to the growth rate of winged aphids on cotton
γ_1.P1.P4	Incoming wingless individuals due to the growth rate of wingless aphids on cowpea
γ_2.P2.P4	Incoming winged individuals due to the growth rate of winged aphids on cowpea
θ_1.P2.P3	Incoming wingless individuals due to the growth rate of winged aphids on cotton
θ_2.P1.P3	Incoming winged individuals due to the growth rate of wingless aphids on cotton
ω_1.P2.P4	Incoming wingless individuals due to the growth rate of winged aphids on cowpea
ω_2.P1.P4	Incoming winged individuals due to the growth rate of wingless aphids on cowpea
β.P1.P3	Depletion on cotton plants due to the feeding of wingless aphids
ε.P1.P4	Depletion on cowpea plants due to the feeding of wingless aphids
δ.P2.P3	Depletion on cotton plants due to the feeding of winged aphids
φ.P2.P4	Depletion on cowpea plants due to the feeding of winged aphids
λ_1.P1	Dead wingless aphids
λ_1.*P2*	Dead winged aphids

Five treatments were considered to predict aphid dynamics: t_1) two cotton plants : two cowpea plants in the row, with each row starting and ending with two cotton plants; t_2) two cowpea plants : two cotton plants in the row, with alternate rows starting and ending with two

cowpea plants; t_3) one row of cotton : one row of cowpea; t_4) cotton; and t_5) cowpea, with three replications (Figure 4, topic 2.2.2).

3.2.1.1. Parameter sensitivity analysis

Sensitivity is an important issue in attempting to make predictions for qualitatively different attributes, such as types of dynamics (Perry, Woiwod & Hanski 1993). In order to determine the model parameter sensitivities, the values of all parameters were fixed, except one, which was varied, in order to analyze how the aphid model reacted to this variation (Figure 9).

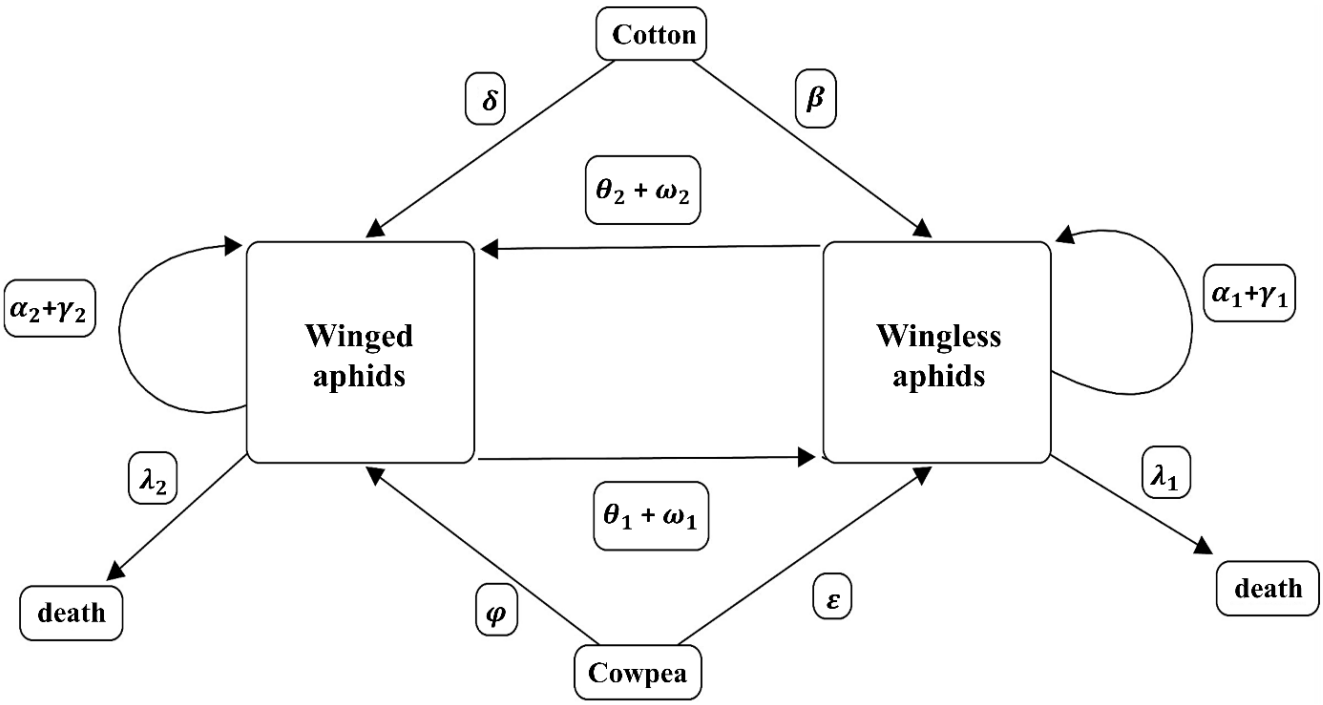

Figure 9. Schematization of the mathematical model. The parameters correspond to the rate at which the component at the arrow tail is consumed (cowpea and cotton) or another at the arrowhead (winged aphids, wingless aphids and death). Piracicaba-SP: 2014

3.2.1.1.1. Cotton aphid

In descending order, the output sensitivity of the output model for *A. gossypii* is shown in the form: $\delta > \beta > \theta_2 > \alpha > \gamma > \alpha_2 > \varphi > \omega_2 > \theta > \gamma_2 > \omega > \varepsilon > \lambda > \lambda_2$.

3.2.1.1.2. Cowpea aphid

In descending order, the output sensitivity of the output model for *A. craccivora* is presented in the form: $\varepsilon > \varphi > \theta_2 > \gamma > \alpha > \delta > \theta > \omega > \beta > \omega_2 > \gamma_2 > \alpha_2 > \lambda > \lambda_2$.

3.3. Results and discussion

The fits of the population growth rates over time are shown in Figure 10 (*A. gossypii*) and Figure 11 (*A. craccivora*). The population dynamics of the two species behaved similarly, with an initial increase (35 to 40 days) followed by a rapid decay at 49 days (Figures 10 and 11). This pattern probably reflects a synchrony between aphid populations and food availabilities. This behavior is typical of situations when food resources are limited (Pollard & Rothery 1994), as was the case in our study. When the populations of *A. gossypii* and *A. craccivora* were small, they increased until the food resources were exhausted, which resulted in a negative growth rate. The decay was smoother for the aphids on cotton intercropped with cowpeas, compared to a sole crop, probably because the intercropping systems reduced the aphid pressure on plants compared to the sole system.

As shown in Figure 10, in sole cotton (t_4) both wingless (13,377 aphids) and winged (3,599 aphids) cotton aphids reached higher population peak than in crop system t_1 (9,848 wingless aphids; 2,208 winged aphids), crop system t_2 (8,299 wingless aphids; 1,756 winged aphids), and crop system t_3 (13,158 wingless aphids; 2,298 winged aphids). The lowest peak for the cotton aphid population was found in crop system t_2 (8,299 wingless aphids; 1,756 winged aphids). In the sole cotton (t_4), t_1 and t_3 crop systems, wingless *A. gossypii* peaked at 42 days, while in crop system t_2 the cotton aphid peaked at 35 days after the plant infestations. The winged *A. gossypii* peaked at 35 days in sole cotton (t_4) and also in crop system t_1, while in crop systems t_2 and t_3, the cotton aphid peaked 35 days after the plant infestations.

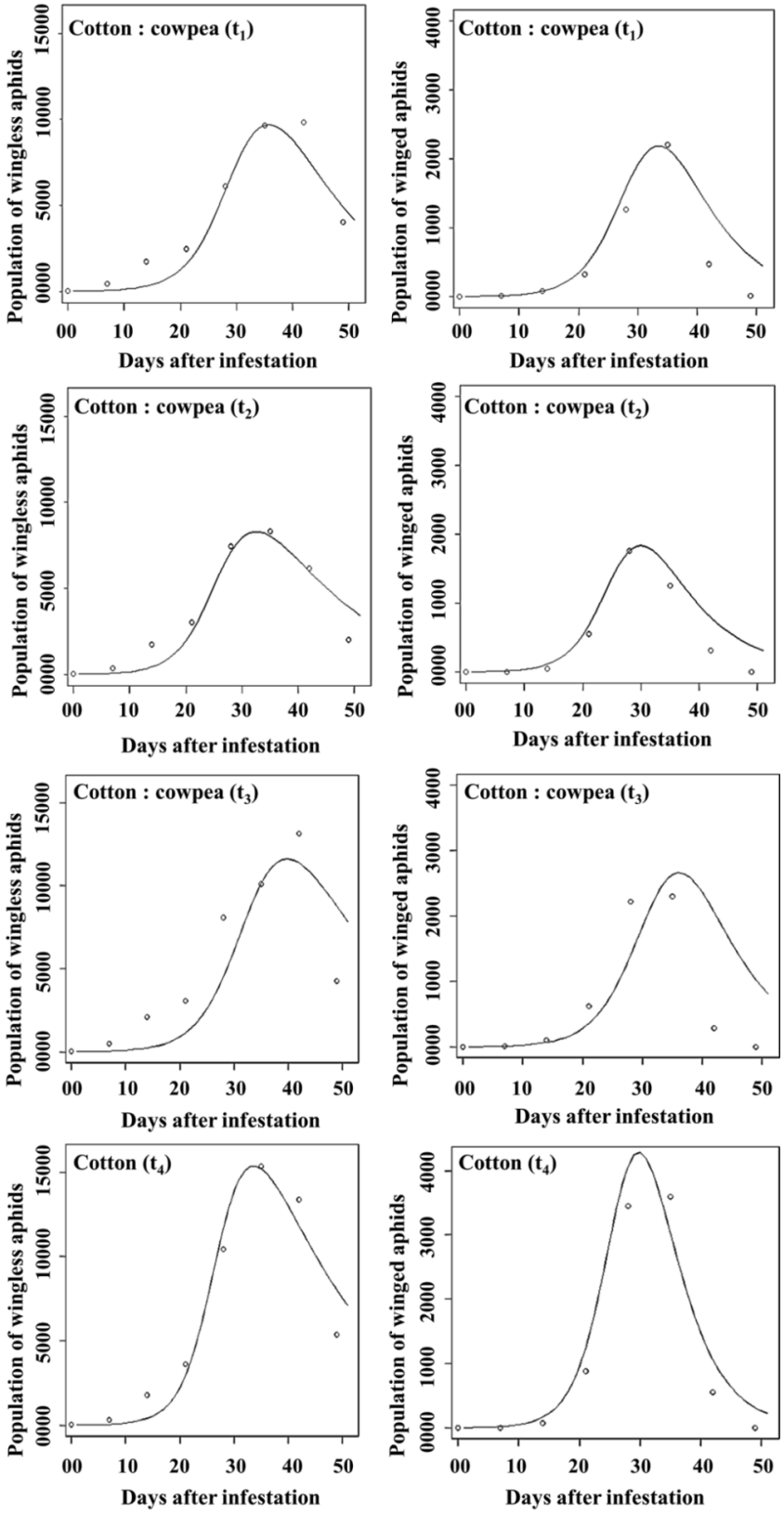

Figure 10. Observed data set (open circles) and model prediction (solid line) for the population dynamics of wingless (left) and winged (right) *A. gossypii* over time for each crop system. Each data point represents the total number of aphids (wingless or winged) on all leaves and reproductive structures of nine cotton plants. Piracicaba – SP: 2014

Both wingless and winged forms of *A. craccivora* showed the numerically highest population peaks in sole cowpea (t_5) (8,150 and 2,900 aphids, respectively) and lowest peaks in the crop system t_2 (4,774 and 1,576 aphids, respectively). The population peaks of wingless and winged *A. craccivora* in sole cowpea (t_5) and in crop systems t_1, t_2 and t_3 occurred at 35 days after the cowpea infestations (Figure 11). These results indicate that the sole cowpea crop hosted numerically more *A. craccivora* than the cowpea intercropped with cotton. The results obtained in this study agree with those reported by Mitiku, Chala & Beyene (2014) who used intercropping of plants to reduce aphid pressure. Intercropping of brassica crop plants confers advantages, such as greater leaf mass and less leaf damage caused by sucking insects (Pahla et al. 2014). In a sole-cotton system, *A. gossypii* populations peaked between 74 and 95 days, whereas in a cotton-fennel intercropping system, populations of this aphid peaked between 74 and 102 days (Fernandes et al. 2013). Populations of *A. gossypii* peaked on 77 days on kale plants (*Brassica oleraceae* Linnaeus) (Resende et al. 2004). These findings are consistent with those of Parajulee, Montandon & Slosser (1997), who described similar data to aphid population peaks in an intercropping system containing cotton, wheat (*Triticum aestivum* Linnaeus), sorghum [*Sorghum bicolor* (Linnaeus) Moench], and rapeseed (*Brassica napus* Linnaeus). On the other hand, populations of *A. gossypii* may peak at different stages of plant growth and development (Afshari, Soleiman-Negadian & Shishebor 2009).

The population growth curves for *A. gossypii* on cotton plants at similar physiological ages behaved similarly (Celini & Vaillant 2004). Resende et al. (2004) linked aphid population fluctuations to the action of predators showing that the presence of predators causes the aphid population to drop. However, Kindlmann & Dixon (1996) explained that aphid dynamics do not exhibit a definite pattern but vary throughout the year, and that these dynamics can be similar or different depending on the mechanisms to plant selection used by the insects. Similar patterns for aphid population dynamics, with an exponential increase and decrease of a population were reported by Ullah et al. (2014). These authors also noted that aphid populations on crops can increase during the vegetative growth phase of the plants; however, a population may decline due to reduction of plant quality, mycoses, and senescence (Honek & Martinkova 2004). This may explain our observation since many plants started the senescence stage at 42 days after the aphid infestation began. However, further studies will be necessary for a better understanding of population dynamics of aphids, taking into account different crop systems.

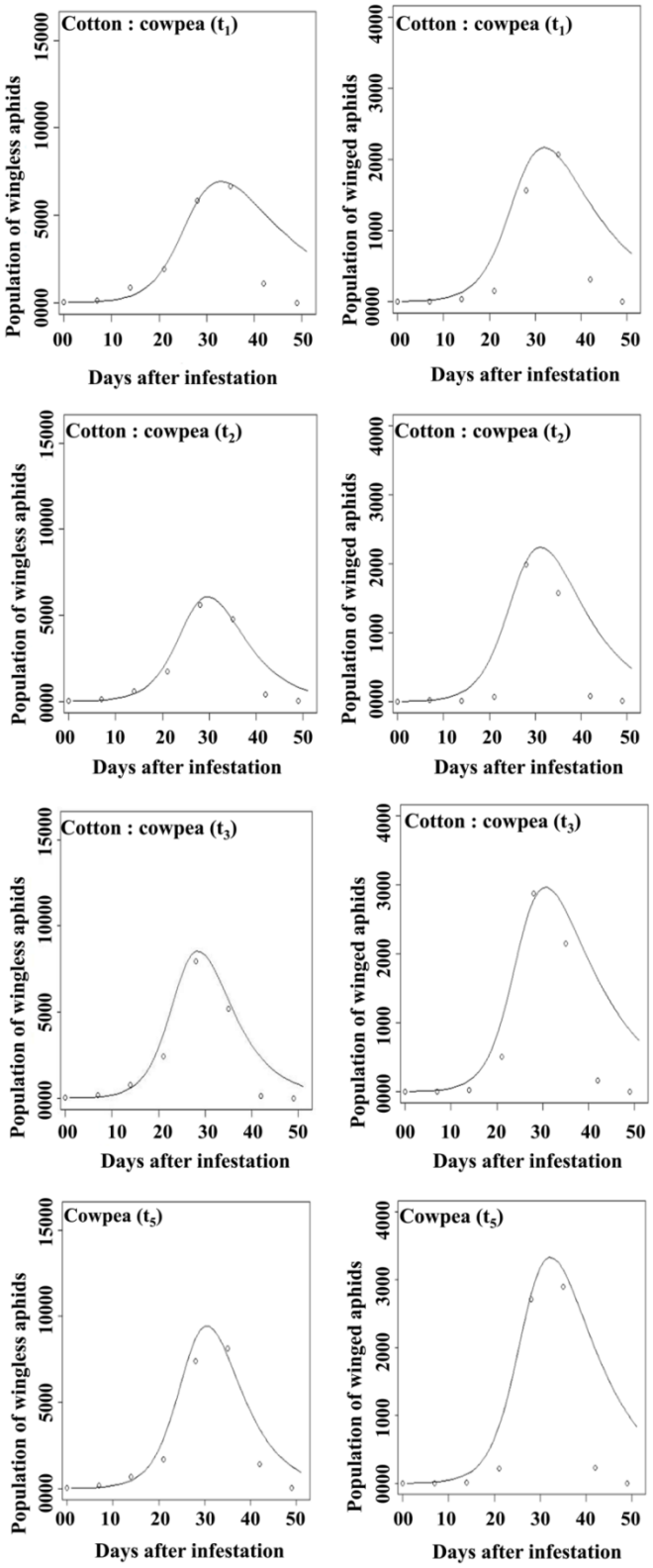

Figure 11. Observed data set (open circles) and model prediction (solid line) for the population dynamics of wingless (left) and winged (right) *A. craccivora* over time for each crop system. Each data point represents the total number of aphids (wingless or winged) on all leaves and reproductive structures of nine cowpea plants. Piracicaba – SP: 2014

The corresponding values of each parameter used for each simulation are listed in Tables 4 and 5. The values of each parameter were defined by using the interpolation method. Taking into account the biological differences between the two species, we assumed that *A. gossypii* could not show a higher feeding rate on cowpea than on cotton, and the reverse for *A. craccivora*.

Table 4. Parameter values for each crop system to simulate the population dynamics of *A. gossypii*. Piracicaba-SP: 2014

Parameters	Only cotton (t_4)	t_1	t_2	t_3
α_1	0.004700	0.011000	0.011800	0.009500
α_2	0.009000	0.012300	0.013500	0.012200
θ_1	0.007000	0.004000	0.007000	0.004000
θ_2	0.001100	0.001000	0.001100	0.005000
γ_1	-	0.001500	0.001000	0.001000
γ_2	-	0.000200	0.000200	0.000200
ω_1	-	0.001500	0.001000	0.001000
ω_2	-	0.000200	0.000200	0.000200
λ_1	0.070000	0.128000	0.090000	0.095000
λ_2	0.250000	0.200000	0.160000	0.200000
β	0.000008	0.000010	0.000017	0.000008
ε	-	0.000003	0.000002	0.000002
δ	0.000008	0.000010	0.000014	0.000009
φ	-	0.000001	0.000001	0.000001

The model resulted in a good prediction for the population dynamics of *A. gossypii* and *A. craccivora*, and also for all crop systems ($p > 0.90$) (Figure 12).

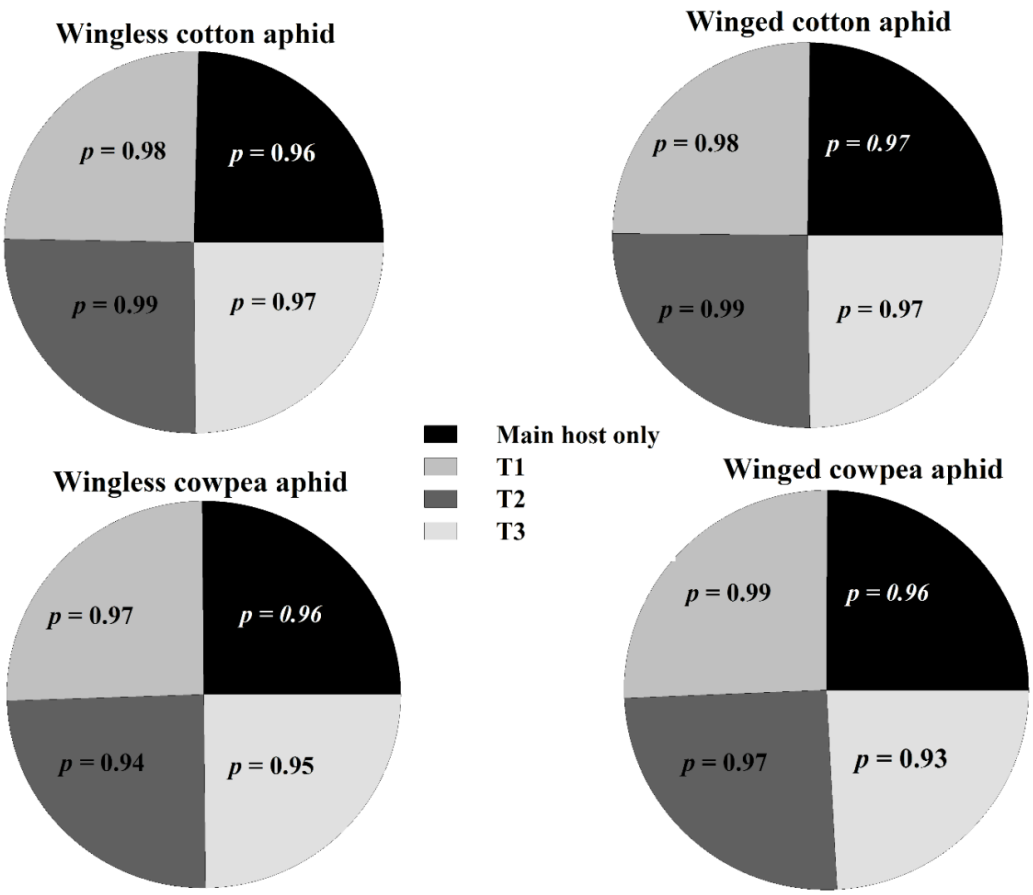

Figure 12. Fit of *p*-values for each simulated situation, using Fisher's exact test. Piracicaba-SP: 2014

The results, shown in Figures 10 and 11, are consistent with the catastrophe theory models of Kot, Lewis & Driessche (1996) and Piyaratne et al. (2014). The fit of the aphid growth rate, in all cases, followed an exponential pattern, with one peak and a subsequent decline in the aphid population. This may indicate that the time period was important, because after the aphid infestations, the occurrence of events was dependent on the time elapsed. Other factors that were not included in this study but that should be considered in future field research are abiotic factors, such as the mean and cumulative rainfall during the growing season.

3.3.1. Sensitivity analysis for cotton aphid and cowpea aphid

The sensitivity analysis for *A. gossypii* demonstrated that the main parameters that influenced the aphid populations were those related to cotton consumption (δ and β) (Table 3). This showed that the availability of cotton plants and the consumption rate regulated the

population dynamics of this aphid, and explains why the aphid population dropped rapidly when the values of δ and β were increased, i.e. increasing the consumption rate. Since cotton is the main host of *A. gossypii*, this result was expected.

In general, the analysis also showed that the influence of parameters related to the consumption of cotton and cowpea by wingless aphids was stronger than the consumption by winged aphids. One possible explanation is that the initial release of only immature aphids on each plot favored the proliferation of larger numbers of wingless aphids; however, winged aphids were produced by their wingless parents in the cotton crop systems over time.

Likewise, just as with *A. gossypii*, the population dynamics of *A. craccivora* was regulated predominantly by the rates of consumption on its main host, in this case, the cowpea (ε and φ) (Table 4). However, the sensitivity of *A. craccivora* for both parameters was higher than the sensitivity of *A. gossypii* for δ and β. Considering the biology of the two species, this result was expected since the consumption of *A. craccivora* on cowpea plants was higher than that of *A. gossypii* on cotton plants, consequently accelerating the nutritional depletion of cowpea plants.

Table 5. Parameter values for each crop system to simulate the population dynamics of *A. craccivora*. Piracicaba-SP: 2014

Parameters	Only cowpea (t_5)	t_1	t_2	t_3
α_1	-	0.001000	0.001000	0.001000
α_2	-	0.000200	0.000200	0.000200
θ_1	-	0.001000	0.001000	0.001000
θ_2	-	0.000200	0.000200	0.000200
γ_1	0.008700	0.012000	0.018000	0.020000
γ_2	0.001900	0.003000	0.004000	0.004000
ω_1	0.008000	0.011000	0.010000	0.020000
ω_2	0.001900	0.005000	0.004000	0.004000
λ_1	0.250000	0.100000	0.260000	0.260000
λ_2	0.130000	0.120000	0.150000	0.116000
β	-	0.000002	0.000002	0.000002
ε	0.000008	0.000018	0.000013	0.000011
δ	-	0.000001	0.000001	0.000001
φ	0.000009	0.000014	0.000010	0.00001

As with *A. gossypii*, the population of wingless *A. craccivora* had more influence on the model than the population of winged aphids. Malaquias et al. (2015) presented information to predict aphid outbreaks stating that it is useful for developing phenological models based on relationships involving temperature and development rates, facilitating the prediction of outbreaks of *Hyadaphis foeniculi* (Passerini) (Hemiptera: Aphididae) in fennel (*Foeniculum vulgare* Miller). Adetiloye (1985) used mathematical models comparing intercropping in different crop systems to elucidate the advantages of the mixture of plants, taking productivity into account; however, the relationship between insect pests and the plants was not studied. Aphids pose a significant challenge to food production (Bell et al. 2015). For this reason, structured models are commonly used to examine their population dynamics (Tenhumberg et al. 2009). The present results found using mathematical models to describe aphid growth rates are important since they can help the understanding of population dynamics of different aphid species in sole crops of cotton and cowpea, and in cotton intercropped with cowpea. Knowledge of sensitivity analysis and insect pest dynamics is essential for the establishment of integrated pest management. Also, modeling of dynamics can predict crop damage (Jonsson et al. 2014). The fitted model can also help to predict the timing of aphid peaks in each crop system. Prediction of aphid peaks is an important tool for ecological studies, which can also be useful for field crops (Malaquias et al. 2015).

3.4. Conclusions

The insights gained may be useful in decision-making, implementing controls, and determining the timing and the size of population peaks for these important cotton and cowpea pests. The simulations using these models are a new approach for short-term prediction of cotton-aphid or cowpea-aphid population dynamics in sole crops and cotton intercropped with cowpea. However, the models developed in this study require field testing before reaching their full potential for predicting the population dynamics of *A. gossypii* and *A. craccivora* in sole and in intercropping systems.

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4. COTTON-COWPEA INTERCROPPING DESIGN INCREASE *Cycloneda sanguinea* (COLEOPTERA: COCCINELLIDAE) ESTABLISHMENT AND PLANT PRODUCTIVITY

Abstract

Adults of *Cycloneda sanguinea* (Linnaeus, 1763) (Coleoptera: Coccinellidae) may disperse on cotton and cowpea plants, where they can be fed and reproduce. This study was carried out with the objective to evaluate the impact of cropping systems on *C. sanguinea* establishment and on plant productivity, aiming at any optimal arrangement for predator conservation and multiplication, contributing to implementation of cotton and cowpea integrated pest management. Cotton plants with colored fibers (BRS Safira cultivar) and cowpea (BRS Itaim cultivar: upright) were cultivated in greenhouse conditions. Cotton and cowpea were infested with *Aphis gossypii* Glover, 1877 and *Aphis craccivora* Koch, 1854 (Hemiptera: Aphididae), respectively. Ladybug predators were marked and released on the crops. Their dispersal on sole colored cotton (t_4) and cowpea (t_5) systems and on colored cotton-cowpea intercropped systems (t_1, t_2 and t_3) was evaluated. All ladybirds were recaptured, counted and discarded. The eggs deposited by females during the movement experiment were considered. The aphids as well as the predator progenies remained on the plants. Other predators were released during the reproductive phase of the plants. Predator progenies and eggs, as well the wingless and winged aphids were respectively quantified on plants per plot. It was found that the abundance of ladybird progeny and cotton productivity was higher in intercropping t_1. The results can be useful to predict the impact of intercropping systems on *C. sanguinea* progeny establishment.

Keyword: *Cycloneda sanguinea*; Progeny; Productivity; Movement; Flowers; Preference

4.1. Introduction

Continuous utilization of area with sole crops can contribute to soil degradation. Intensive use of no selective insecticide and increase of pests causes damage to plants and reduces overall productivity (Chandler et al. 2011; Naab et al. 2017; Nwaiwu 2017). The losses in terms of productivity as well as the use of expensive pesticides increase production cost. In addition, insecticides raise several types of environmental issues and can also cause mortality of natural enemies in the agroecosystem (Chattopadhyay, Banerjee & Mukherjee 2017; Mkenda, Ndakidemi & Mbega 2017). The diversification of area with different types of crops can be beneficial for the agroecosystem since it allows more interactions among arthropods and below ground food webs, providing shelter, food, acting as refuges for natural enemies that directly reduce pest populations and related plant damage (Straub et al. 2014; Ramalho et al. 2015; Vinod et al. 2016).

Some cotton cultivars (*Gossypium hirsutum* Linnaeus r. *latifolium* Hutch) have been developed to aggregate value for sub products and to reduce cost with water, dying during the

industrial process of final product (Ramalho et al. 2012a). In the Northeast of Brazil, the utilization of cotton with colored fibers intercropping systems is fundamental to agroecosystems because it can maintain diversity of natural enemies and control pest populations providing socioeconomic, ecological and environmental benefits that can contribute to agribusiness (Fernandes et al. 2012; Fernandes et al. 2013; Fernandes et al. 2015). Interestingly, some studies have shown that cotton-fennel intercropped systems increase natural enemy populations as well as the distribution of pests in plants and the interspecific associations of natural enemies when compared to sole crops (Fernandes et al. 2013; Fernandes et al. 2015). The knowledge about the impact that intercropping systems could have on the dispersal and establishment of *Cycloneda sanguinea* Linnaeus (Coleoptera: Coccinellidae) predators is essential to promote the design of predator conservation programs (Choate & Lundgren 2014; Otsuki & Yano 2014), and to provide opportunities for the presence of one key species that can enhance agroecosystem sustainability (Baloch et al. 2016; Lopes et al. 2016; Altieri 2017).

The predator *C. sanguinea* and other generalist predators can have strong and positive responses to specific plant diversity in cotton systems intercropped with cowpea due to the abundance of flowers and/or the diversity of aphid species present in such intercropped systems (Dassou & Tixier 2016; Pruchniewicz 2017; Seko et al. 2017). This study was carried out with the objective of evaluating the impact of cropping systems on *C. sanguinea* establishment and on plant productivity, also aiming to suggest implementation of cotton and cowpea integrated pest management, taking into account different arrangements for predator conservation and multiplication.

4.2. Material and methods

4.2.1. Studied location, cotton and cowpea cultivars

As the experiment performed for the aphid dynamics study, this one was also conducted under greenhouse conditions at the Department of Entomology and Acarology, Luiz de Queiroz Agriculture College, University of São Paulo (ESALQ/USP), Piracicaba, Brazil. Cotton plants with colored fibers (BRS Safira cultivar) and cowpea (BRS Itaim cultivar: upright) were cultivated in greenhouse conditions. Plants were irrigated daily and crop handling (fertilization and elimination of weed in the treatment) was performed whenever necessary. Two phenological plant phases, namely the end of the vegetative phase

and the beginning of the cotton reproductive phase (emergence of first flower), were chosen to evaluate predator's preferences.

4.2.2. Insects rearing

As explained previously in topic 2.2.1, winged and wingless individuals of two species of aphids, *A. craccivora* and *A. gossypii* were reared in laboratory conditions. *C. sanguinea* adult males and females collected in the field were reared on Petri dishes (5, 9 and 16 cm) under laboratory conditions (Figure 13). They were fed a*d libitum* with frozen eggs of *Ephestia kuehniella* (Zeller, 1879) (Lepidoptera: Pyralidae), water (25%) + honey (50%) + brewer's yeast (25%) solution. As an additional source of food, aphid specimens of *A. craccivora* and *A. gossypii* were added to the Petri dishes weekly. *C. sanguinea* larvae (F1) hatching from the eggs laid by females from field were also fed with *E. kuehniella* eggs and individuals of both species of aphids. Both larvae and adults were maintained in a climatic chamber (BOD) at 25±1ºC, 70±10% relative humidity, and 12-hour photophase. Adult individuals of the first laboratory generation of predators were individually placed in Petri dishes under the same conditions as the individuals collected from the field until used in the greenhouse experiment.

Figure 13. *Cycloneda sanguinea* rearing under laboratory conditions

4.2.3. Plants and experimental design

The experimental design was the same as the one described in topic 2.2.2. To keep the insects within our experimental setting (topic 2.2.2), all treatments were kept inside a transparent cage protected with white tissue (Figure 5A).

4.2.4. Insect release, recapture and count

The time and proceeding of aphid release was the same showed in topic 2.2.2. However, the aphids were only counted 77 days after plant sprouting (Figure 15). To evaluate predator dispersal during the vegetative phase of the plants, three days after the aphids were released, 75 adult ladybugs were marked with corrective ink and released on the plants (Figure 14). The released individuals were equally distributed among the treatments: 5 individuals per treatment. The plant chosen to release the ladybugs was different from the plant chosen to release the aphids within each treatment.

Figure 14. *Cycloneda sanguinea* marked and released under greenhouse condition. Female (A) and male (B)

Three, 12 and 24 h after the predators were released, their location was noted. To avoid counting individuals more than once at each time observation interval (due to their ability to fly between treatments while the observations were conducted), all the marked adult ladybirds found in each treatment were captured and stored in a Petri dish until the

observations of all the treatments were finished. After the observations were completed, the ladybirds were released again in the same treatment in which they had been found. For the last time observation interval, i.e. 24 h, all the marked ladybirds were discarded after being recaptured. The aphids as well as the predators' progenies, eggs laid by marked predators, remained on the plants.

To evaluate predator dispersal during the reproductive phase of the plants, 75 new adult ladybirds were again marked and released as in the vegetative phase, after the first pod maturity in the cowpea plant (Bastos et al. 2002; Ibrahim, Auwalu & Udom 2010) and after the first flowers (Ritchie et al. 2004) emerging in the cotton plant (approximately 65 days after the plants sprouted). The release of adult predators was conducted as in the vegetative phase and their dispersal was determined by the same procedure as the one explained for the vegetative stage (Figure 15).

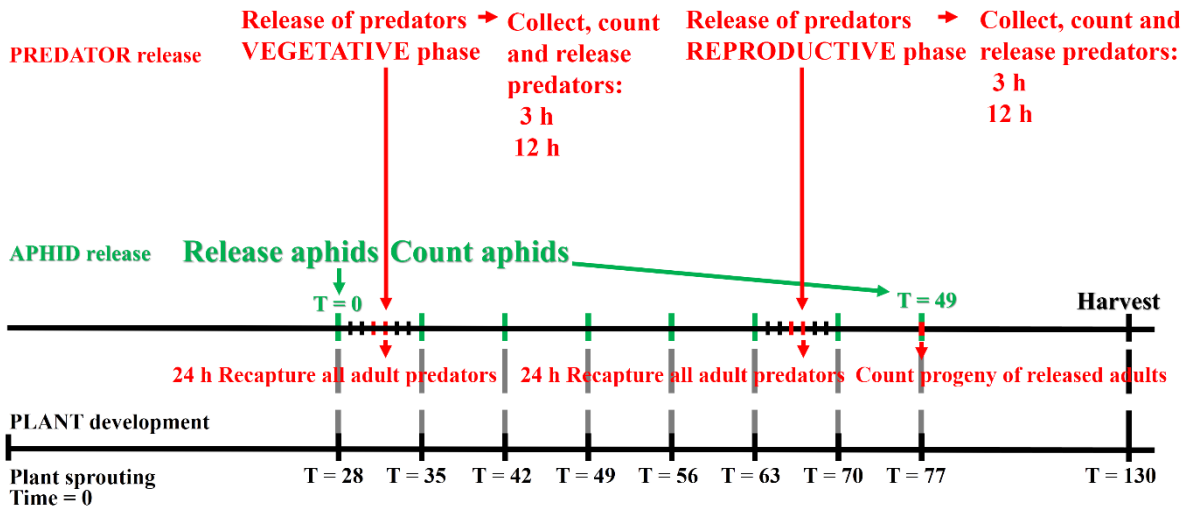

Figure 15. Schematization of insect release and count

4.2.5. Predator establishment: abundance of new emerging adults and eggs

Seventy-seven days after plant sprouting, the same-stage predator progenies were respectively quantified in all plants per treatment. In addition, the number of eggs laid by predators was counted in one plant per treatment.

4.2.6. Plant productivity

Plant productivity was measured 130 days after plant sprouted for three cotton and three cowpea plants per plot. The productivity was measured by weighting the open bolls for cotton plants and seeds for cowpea plants.

4.2.7. Data analysis

In this study i) the cropping preference of *C. sanguinea*, ii) the cropping preference of *C. sanguinea* progeny: F1, iii) the reproductive success of predators (progeny of progeny: F2), and iv) the productivity of cotton and cowpea plants were analyzed. All statistical analyses were performed using R software, version 3.1.3 (R Development Core Team 2015) and the packages *nnet* (Ripley & Venables 2016), *plyr* (Wickham 2016), *tibble* (Müller, Wickham & Francois 2017), *dplyr* (Wickham 2017) and *pscl* (Jackman 2015).

We performed a multinomial logit model for nominal categorical response variables to determine the preference of released *C. sanguinea* predators for the different cropping systems over time (i.e. the 24 h period). The response variable of the model was the number of predators in each cropping system. The model included as fixed factors time, plant phase (vegetative and reproductive), and the coordinates *x* and *y* of the cropping systems.

To test the preference of *C. sanguinea* progeny for the different cropping systems a generalized linear model (GLM) with a Poisson error distribution and a log link function were performed. Overdispersion was observed and standard errors using a quasi-GLM model were corrected. The response variable of the model was abundance of progeny. The fixed factors included were plant (cotton or cowpea), cropping system (t_1 to t_5), abundance of winged prey, abundance of wingless prey, and the coordinates *x* and *y* of the cropping systems. For all analysis, p-values of the models using likelihood ratio tests were obtained.

The reproductive success of predators using the eggs as an estimate for the reproductive success was analyzed. To analyze the abundance of eggs, it was performed a zero altered Poisson model or hurdle model since the abundance of eggs had much more zeroes than could be expected with a Poisson model. Thus, the abundance of eggs was modeled using two distinct processes: the first process explains the presence or absence of eggs (Binomial process), and the second process explains the number of laid eggs (truncated Poisson process). The response variable for the Binomial process is the presence or absence of eggs in a particular cropping system, while for the truncated Poisson process it means

abundance of eggs (omitting the zeroes). Both models included the abundance of predators as fixed factors.

Finally, to analyze whether the plant productivity was different for each treatment, plant, and the combination of the two, a two-way ANOVA was performed. The response variable of this model was plant productivity. The variable was previously standardized because the productivity scale was different for both plants: weighing open bolls for cotton and weighing seeds for cowpea. The model included as fixed factors cropping system, plant, the interaction of cropping system and plant, and the coordinates *x* and *y* of the cropping systems.

4.3. Results

4.3.1. Proportion of individuals on plants over time

It was observed that independently of treatments, the proportion of released adults found within all treatments was higher than 0.50 in both vegetative and reproductive phase of the plants (Figure 16). After 3, 12 and 24 h the proportion of *C. sanguinea* within the treatment was 0.79, 0.64 and 0.81 in vegetative phase and 0.72, 0.56 and 0.59 during reproductive phase, which indicates that several individuals may both have leave and remain on the plants of cotton and/or cowpea.

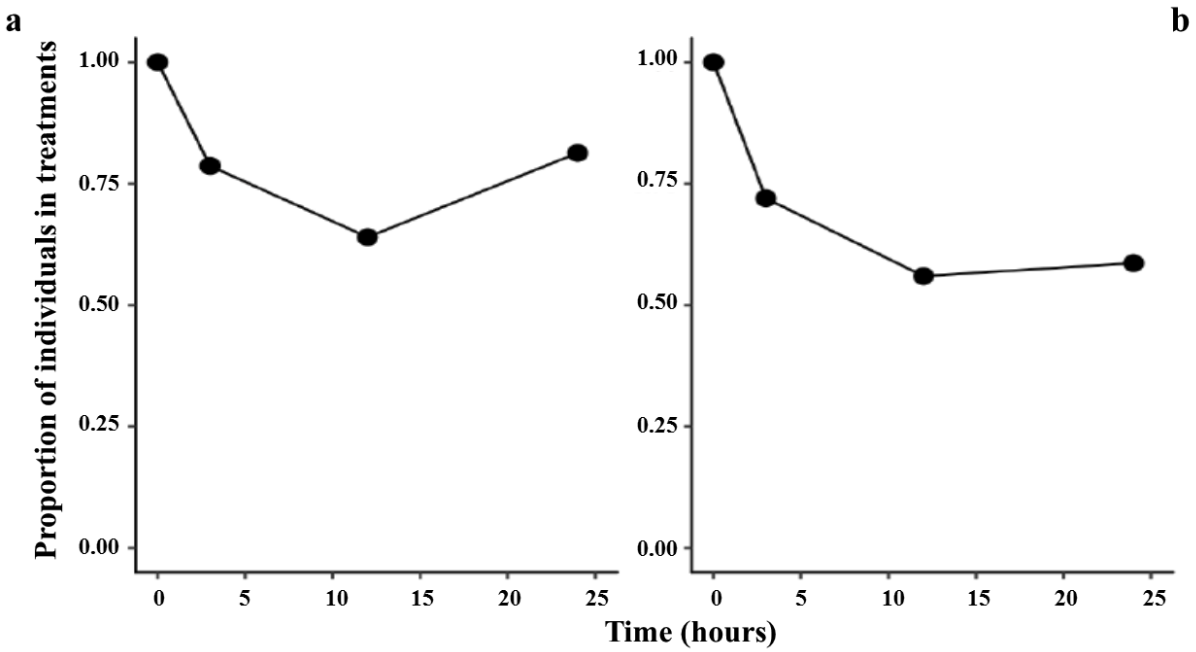

Figure 16. Proportion of adult ladybird released and recaptured on sole and intercropping systems of cotton and cowpea over time. Piracicaba-SP: 2014

4.3.2. Logit multinomial model for predator movement study

Table 6 documents the summary for each parameter of the logit model. This result was useful to predict ladybird's movement across treatments, over time, phase of plant or spatial position.

Table 6. Parameters of the logit models. Piracicaba-SP: 2014

Treatment	Intercept	Phase	Time	*x*	*y*
t_1/t_5	0.573	-0.185	-0.001	-0.233	0.073
t_2/t_5	1.141	-0.077	-0.002	-0.625	-0.133
t_3/t_5	0.218	-0.089	-0.014	0.089	-0.155
t_4/t_5	-1.362	0.215	-0.032	0.591	-0.072

Although there was no significant attraction of predators for treatments, a slight tendency for them to disperse increasingly in the treatment t_1 (intercropping systems) and in the t_5 (sole cowpea) in response to time was found (Figure 17).

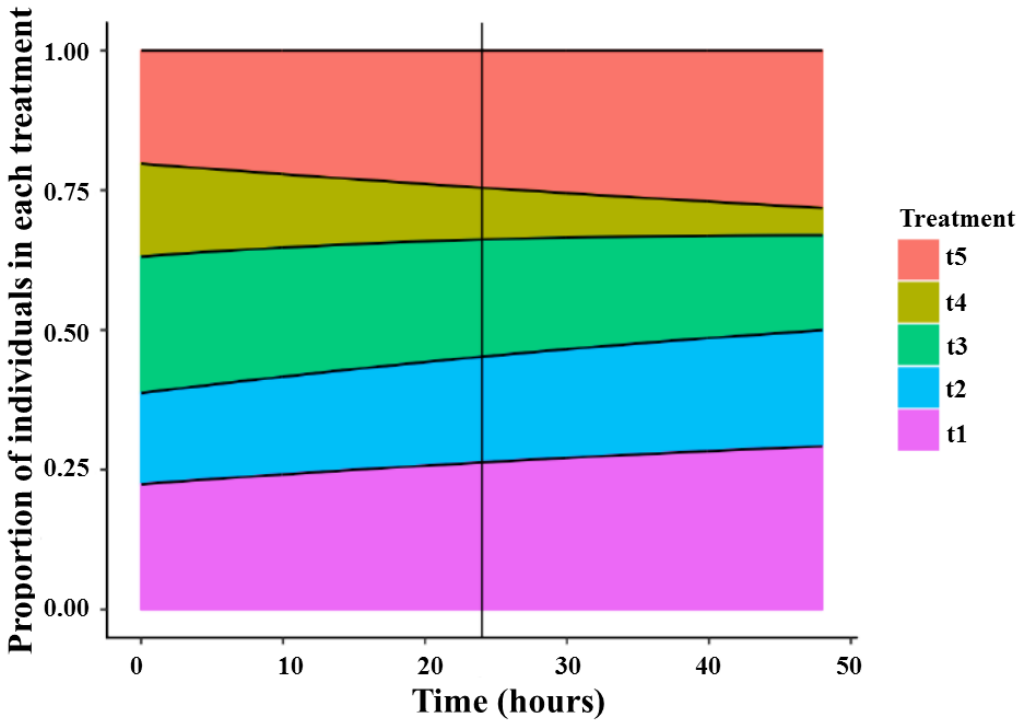

Figure 17. Proportion of adult ladybirds recaptured in each mono-cropping and intercropping system of cotton and cowpea over time. The vertical lines indicate the duration of experiment. Piracicaba-SP: 2014

The logit model explained the spatial movement of predator and the side *x* (Table 7) was the best for insect dispersal within greenhouse conditions (LRT = 102, DF = 4, *P* value < 0.001, Table 7).

Table 7. Logit model summary. Piracicaba-SP: 2014

Variable	LRT	DF	*P* value
Phase	1.68	4	0.794
Time	4.35	4	0.360
x	102.00	4	<0.001
y	2.26	4	0.687

4.3.3. Dispersal of predators

The spatial position of the treatments (Figure 18), allowed the determination of the specific localization of ladybirds through time during both the vegetative and the reproductive phases of the plants. In the vegetative phase, it was observed that 12 h after ladybirds were released, most predators were located in treatment t_1, and after 24 h most predators were located in both t_1 and t_5. During the reproductive phase most predators were located in treatment t_5. On the other hand, fewer predators were found on treatment t_4 during vegetative phase or on t_2, t_3 and t_4 during the reproductive phase of the plant.

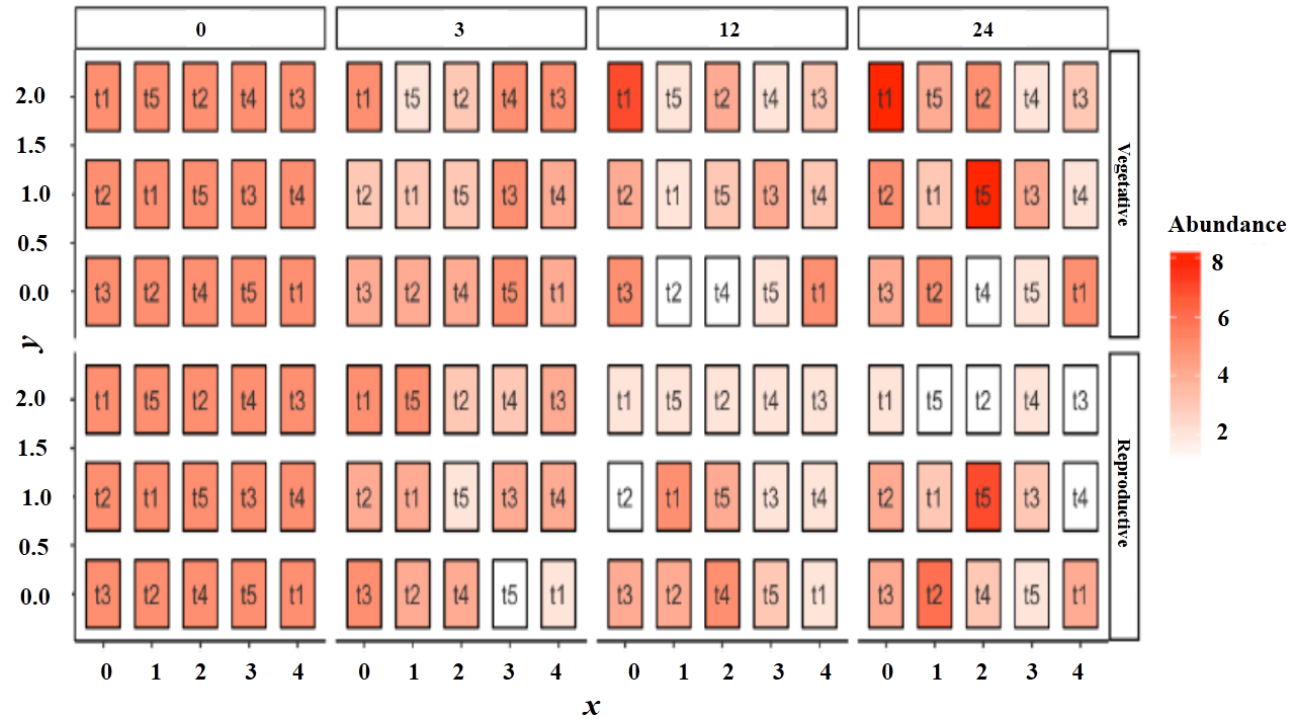

Figure 18. Schematization of predator movement within greenhouse experiment (color of each treatment: t_1, t_2, t_3, t_4 and t_5, the most red indicates higher abundance; on the other hand, the white one indicate less abundance) and spatial coordinates of the plots (*x*: 0 to 4 treatment position and *y*: 0 to 2 treatment distance among block: m). 0, 3, 12 and 24h are the time which the released ladybirds were recorded within each treatment. Piracicaba-SP: 2014

4.3.4. Abundance of predator progeny

The abundance of predator progeny was different among treatments (LRT = 20.48, DF = 4, *P* value < 0.001), but there was no difference between plant species, abundance of winged or wingless prey and spatial position (Table 8).

Table 8. Progeny model summary. Piracicaba-SP: 2014

Variable	LRT	DF	*P* value
Plant	0.010	1	0.944
Treatment	20.48	4	<0.001
Winged prey	0.310	1	0.579
Wingless prey	0.200	1	0.651
x	2.690	1	0.101
y	3.630	1	0.057

The highest number of new emerging adults was found in treatment t_1 (Figure 19). The results suggest this treatment was the best for the establishment of *C. sanguinea* progeny.

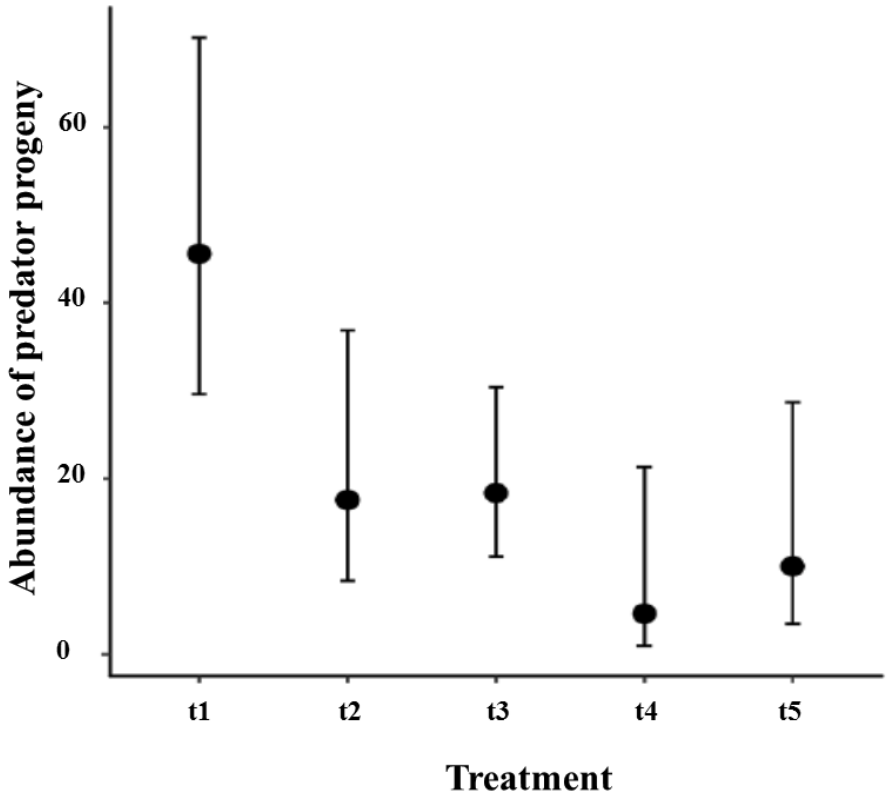

Figure 19. Abundance of predator progeny within each treatment (no). Which t_1, t_2 t_3 = cotton cowpea intercropping systems, t_4 = sole cotton and t_5 = sole cowpea. Piracicaba-SP: 2014

4.3.5. Reproductive success of predator progeny

Taking into account the reproductive success, it was found that the abundance of predators was well fitted to both Binomial and truncated Poisson model (Table 9). This indicates that reproductive success can be influenced by the number of eggs laid by predator in the plant or by the presence or absence of eggs.

Table 9. Hurdle model summary - Binomial and truncated Poisson. Piracicaba-SP: 2014

Variable	LRT	DF	*P* value
Abundance progeny	8.48	1	0.004
	74.7	1	<0.001*

*Truncated Poisson

Regardless of treatments, the variable that explained both the decision to lay eggs and the number of eggs laid was abundance of predator progeny for the same generation. The probability to find eggs in the plants increased as the abundance of predators increased (Figure 20A) and the same result was observed for the number of eggs laid in each plot by *C. sanguinea* predators (Figure 20B).

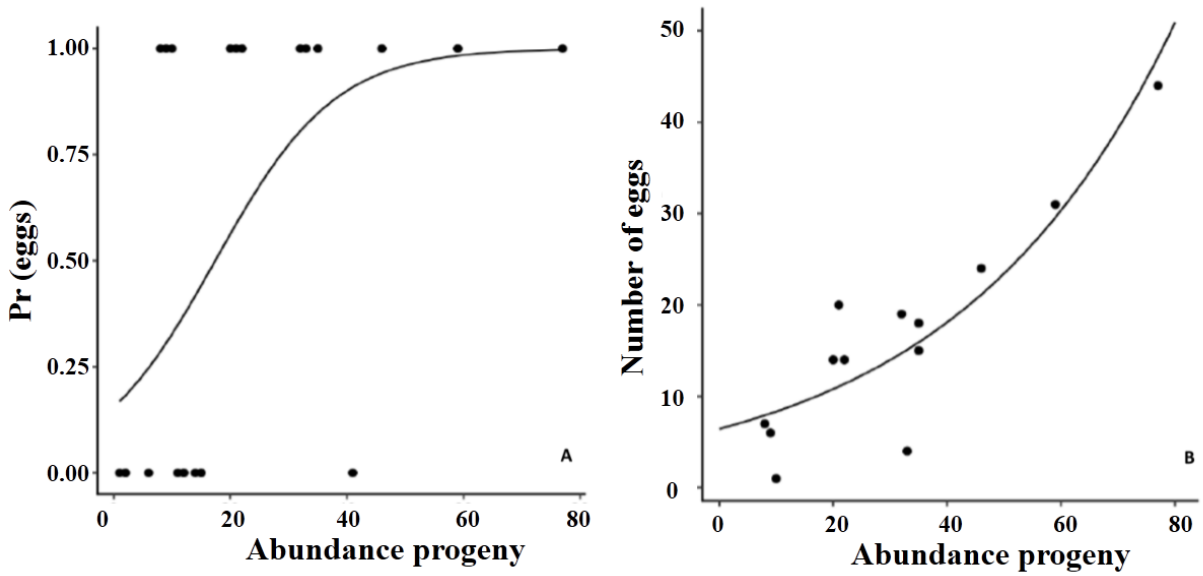

Figure 20. Reproductive success of progeny. Probability to find eggs in the plants (A) and number of eggs laid by predator progeny (B). Piracicaba-SP: 2014

4.3.6. Plant productivity

Regarding the productivity parameter, there was no difference between different plants, i.e. cowpea or cotton (F = 0.20, DF = 1, *P* value = 0.665), or treatment (F = 1.60, DF = 1, *P* value = 0.229). Nevertheless, a significant interaction between treatment and plants was found, when evaluating crop productivity (F = 9.37, DF = 2, *P* value = 0.003, Table 10).

Table 10. Standardized production model summary. Piracicaba-SP: 2014

Variable	SS	DF	F	*P* value
Treatment	2.40	4	1.60	0.229
Plant	0.07	1	0.20	0.665
x	1.87	1	4.99	0.042
y	5.16	1	13.78	0.002
Treatment x Plant	7.01	2	9.37	0.003
Residuals	5.24	14	-	-

Productivity patterns across treatments were different for cotton and cowpea plants: while cowpea productivity was not significantly different among treatments, cotton productivity was highest in t_1 intercropping systems (Figure 21). This result indicates that in this treatment, there was more reproductive structure per plant than in others.

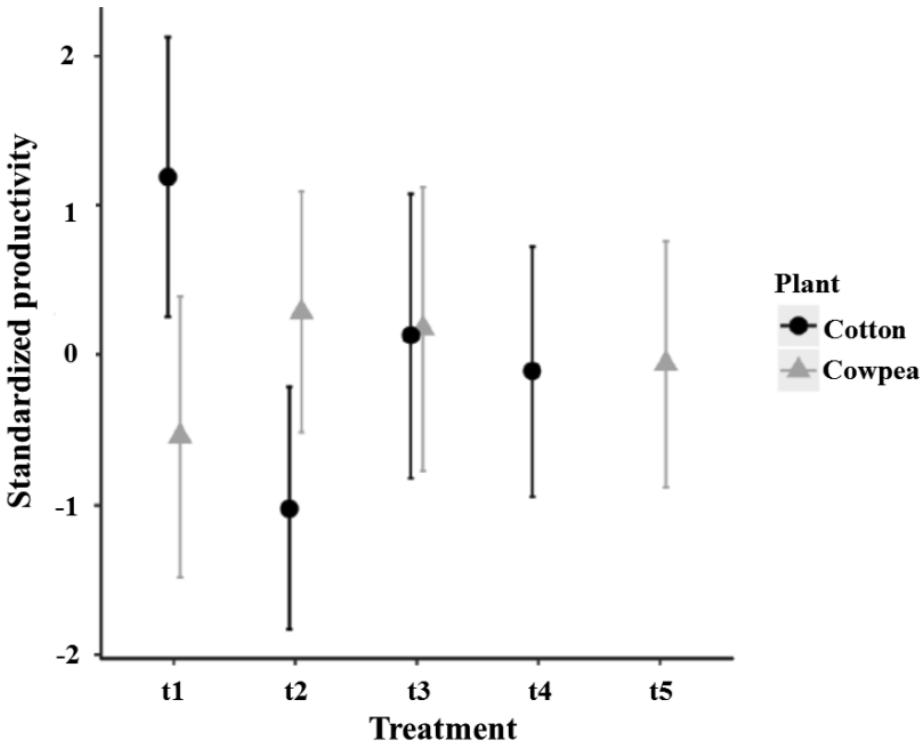

Figure 21. Standardized production of crops under greenhouse condition Which t_1, t_2 t_3 = cotton cowpea intercropping systems, t_4 = sole cotton, t_5 = sole cowpea and standardized production$_{(z)}$ = $X_{\text{cotton or cowwpea}}$ – mean/standard deviation. Piracicaba-SP: 2014

4.4. Discussion

This study revealed that the cropping systems of colored cotton and cowpea can influence *C. sanguinea* reproductive success and cotton productivity. The results found with respect to proportion of released adult predators suggest that, in a short time, individuals remaining within the plot can lay eggs during the movement across the plants, which was important for the progeny establishment over time and plant productivity. This was possible because adult ladybirds are able to eat various prey species while looking for oviposition sites, presuming that females should lay eggs in more suitable sites for offspring development (Sarmento et al. 2007). Although the landscape structure chosen for egg laying may affect the pattern of insect diversity due inter-specific competition, some species of ladybirds can be more abundant, and their progenies may aggregate and accumulate in resource-rich habitat (Egerer et al. 2016); then, *C. sanguinea* can lay eggs next to aphid's colony and the adult progeny can eat the aphids present in plants (Shahruddin & Ba 2017). These results as well as other studies confirm that the multiplication of ladybirds in greenhouse condition for their use in biological control of aphids is possible (Riddick 2017). In fact, the composition of plots can be interesting for ladybird establishments over generations.

The movement of ladybirds across plants can be stimulated by: 1) presence of flowers in the plant, important source of food resources to maintain populations of generalist predators; 2) presence of aphids, important preys of this natural enemy (Seko et al. 2017). As cotton productivity was higher in intercropping $t_{1,}$ and also where ladybird's progeny was most abundant, there was strong evidence that the reproductive structure of plants was important to attraction of insects. It was also found that the influx of ladybirds in plants can be affected by the quality of crops and flowering of cotton (Bastola et al. 2016). This result gives support to the hypothesis that more reproductive structure in plants attracts *C. sanguinea*. In addition, it was found that abundance of predator progeny was the influent variable explaining the results about the presence or absence of eggs on the plants. In other words, the oviposition was higher where there were more individuals of adult ladybirds found in the plants. These were probably associated with factors such as rate of mortality or eggs viability, and larvae density of predator progeny that can eat aphids. It has been observed in literature that natural enemies are directly affected by offspring mortality, as well as the presence of other predators and food source (Sarmento et al. 2007). This played a fundamental role in the access to patches by ladybirds. These results can be useful to estimate the proportion of eggs laid by *C.*

sanguinea in plants within the plots of cotton and cowpea in the same habitat conditions, and consequently, estimate the number of adults to be released.

Although there are some species of generalist ladybirds which show no significance preference among different forms of non-crop habitat (Heimoana et al. 2017), it was found that ladybird abundance and species richness correlate with local and landscape factors (Egerer et al. 2016). This explains the abundance of adult *C. sanguinea* progeny in treatment t_1, indicating that it was the most suitable habitat, where females could find many food sources and few competitors (Kohandani, Le Goff & Hance 2017). There is a study (Seko et al. 2017) that corroborates these results.

Comparing the remaining predators in agricultural plants, it was found that predator *Harmonia axyridis* (Pallas, 1773) (Coleoptera: Coccinellidae) remains in higher numbers in intercropped plants than in sole crops. In terms of pest management, it is believed that cotton-cowpea intercropping systems (t_1) are promising since plant diversification is likely to increase the control of specialist herbivorous by predators, and consequently, increase productivity (Dassou & Tixier 2016). However, this recent study shows that row combination in intercropping systems may influence the results.

On the other hand, some other combinations contribute to the reduction of losses in cottonseed by enhancing predator numbers to suppress pests (Ramalho et al. 2012b; Ben-Issa, Gomez, & Gautier 2017). In fact, taking into account the impact of the intercropping on plant productivity proposed in this study, it was observed that the pattern of the plant productivity (Figure 20) was different, and colored cotton productivity in intercropping t_1 was better than in sole cotton, sole cowpea, or intercropping t_2 and t_3. Similar results were found in literature documenting that intercropping systems of cotton and cowpea increased productivity with land equivalent ratios of 1.4 for the same design used in this study (Rusinamhodzi, Murwira & Nyamangara 2006; Kumar et al. 2017). It was reported that seed cotton equivalent yield within cotton-cowpea intercropping systems (1:1, 1918 Kg ha^{-1}) was higher than in sole cropping (1266 Kg ha^{-1}) (Kumar et al. 2017). The influence of intercropping systems was also investigated in the productivity of plants (Singh et al. 2017), with results indicating that boll weight of cotton-cowpea intercropped (2.86g) was similar to mono-cropping of cotton (2.85g). However, the study carried out by Singh et al. (2017) did not compare the impact of intercropping systems on *C. sanguinea,* and consequently, on plant productivity as measured in our experiment. In this sense, the results found in this study can be useful for other greenhouse studies; however, for a deeper understanding of their impacts on aphids, natural enemies, and plant productivity, further field experiment studies should be conducted.

Vegetation complexity can be characterized by structural aspects (i.e., structural barriers that impede insect dispersal), and by chemical complexity (different allelochemicals), which are often species-specific. Also, diversity within and between habitat patches will strongly affect the expression of these traits (Harvey & Fortuna 2012). Considering the *C. sanguinea* movement during vegetative and reproductive phases, along with cowpea productivity, the analysis carried out in this study predicted that cowpea productivity was similar among treatments. However, predator movement tended to treatment, or within the treatment, where plants of cowpea were planted (t_1 and t_5), except treatment t_2 and t_3, which, in general, were placed far from treatment t_1. As plants have no ability to move away from stressful situations, there are specific defense mechanisms used to face different environmental disturbs (Markovic et al. 2014). These plant responses give support to evaluate insect plant interactions, such as the investigations performed in the present study. It is possible that in sole cowpea or cowpea intercropping t_1, a higher number of plants may release more allelochemicals for attraction of *C. sanguinea* adult, which uses volatile cues to access patch profitability (Sarmento et al. 2007; Salamanca et al. 2015).

A study carried out in 2016 reported that, it is a fact that the abundance of ladybird can be different among plants, and some kinds of crops, which released volatile chemicals, can form the basis of a "push–pull" strategy, contributing for aphid control, due to the attractiveness of natural enemy (Zhou et al. 2016). Our results also showed that cowpea planted in intercropping t_1 and sole cowpea (t_5) was the most important treatment to ladybird's movement probably due to the chemical composition of the plants, which was fundamental to predator attraction during vegetative and reproductive phases. In conclusion, this study enables us to understand how *C. sanguinea* chooses the plots for feeding, oviposition, and progenies establishment. This knowledge can be useful to predict the time of release and multiplication of predator in cotton-cowpea intercropping systems. Consequently, cotton-cowpea intercropping systems could be used as part of IPM strategies to reduce non-selective insecticide use by enhancing predator activity in crop plants at the same time as aphid populations start infesting them (Han, Niu & Desneux 2014; Kohandani, Le Goff & Hance 2017).

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5. SIMULATION OF PLANT BIOMASS AND ARTHROPODS RELATIONSHIP IN CROPPING SYSTEMS OF COTTON AND COWPEA

Abstract

Cotton-cowpea intercropping system can be one of the most important practices for the increase of natural enemies and the reduction of pest numbers. This chapter was written aiming at the analysis of intercropping biomass, as well as arthropods relationship. Initially, a wide review was performed to give support to the development model in order to explain the biomass and the relationship between pest and natural enemies in sole or intercropping systems of cotton and cowpea. It was observed that several previously developed models as well as the model here proposed suggest that the increase in plant biomass and natural enemies depend on the pest number and cropping systems arrangement.

Keywords: Arthropods; simulations; biomass; stability

5.1. Introduction

Cotton (*Gossypium hirsutum* L. r. *latifolium* Hutch) with naturally colored fibers has potential to be used worldwide, particularly in the textile industry. It adds value to the agricultural exploitation by small farmers (Ramalho et al. 2012b). Cowpea (*Vigna unguiculata* Linnaeus Walp.) is an important green legume, green manure, vegetable that enables nitrogen fixation in the soil, and it is also a staple food to meet the protein needs of the Northeastern population in Brazil (Frota et al. 2008; Choudhary et al. 2017). In addition, these agricultural products substantially help generating jobs and incomes for farmers in this Brazilian region. However, cotton and cowpea production in Brazil have been compromised by the constant attack of sucking insects that can cause direct and indirect damage to the plants (Ramalho et al. 2012b). The main sucking insects found in cotton and cowpea are *Bemisia tabaci* Biotype B, (Gennadius, 1889) (Hemiptera: Aleyrodidae), *Aphis gossypii* Glover, 1877 and *Aphis craccivora* Koch, 1854 (Hemiptera: Aphididae). Their control is usually done by using non-selective chemical insecticides that, despite being effective against pests, often cause mortality above 30% in beneficial insect populations (Ullah & Paul 1985; Leite et al. 2010).

Several studies have shown that the agroecosystem diversification may reduce insect pest infestations by using different plant species intercropping in order to obtain ecologically advantageous control (Medeiros, Sujii & Morais 2009; Fernandes et al. 2012; Ramalho et al.

2012a). Well-structured and connected habitat settings may allow species spatial segregation by reducing the interspecific competition (Boeye, Kubisch & Bonte 2014). On the other hand, the use of different plant species in intercropping systems leads to significant changes in the arthropods habitat by favoring natural enemies' (predators and parasitoids) behavior and by negatively affecting insect pest's behavior and development (Gonzaga, Ramalho & Santos 1991). Consequently, it increases agricultural crops' productivity in more than 23% (Ramalho et al. 2012a; Ramalho et al. 2012b; Mitiku, Chala, & Beyene 2014).

Regarding the movement of insects, some intercropping systems may be repellent to pests, whereas others are attractive to natural enemies (Kadam, Kadam & Lekurwale 2014). It is known that the movement of predatory ladybirds in agricultural intercropping systems may occur between two different crops, both of which may benefit from insect influx over time (Bastola et al. 2016). Natural enemies' attraction to certain crops may occur due to several factors, among them, prey availability, plant features from which the resource provision shelter, protection, and food sites stand out (Resende et al. 2012). Plant odors in different types of intercropping systems also work as attractive to natural enemies (Ninkovic & Pettersson 2003). Understanding how arthropods pests and their natural enemies interact in complex agricultural ecosystems such as intercropping systems is essential for pest management programs (Chailleux et al. 2014).

Many mathematical and statistical models can be used to analyze the dynamics of populations enabling the evaluation of the stability of individuals in agroecosystems (Piyaratne et al. 2014; Ngalya & Kuznetsov 2017; Anguelov, Dufourd & Yves 2017a). Nevertheless, the utilization of these models to evaluate the dynamics and plant productivity in intercropping systems of cotton and cowpea is incipient. The utilization of analytic tools to study complex systems as intercropping is important to predict the occurrence of pest and their natural enemies as well as evaluate plant biomass. On the other hand, climatic factors and radiation incidence in agricultural production are relevant elements in the development and analysis of scenarios that can impact farmer income and food security (Willocquet et al. 2008; Carvalho et al. 2017; Donatelli et al. 2017). Modeling is also very useful to evaluate experienced systems, promoting the knowledge and implementation of real systems based in results of predictions (Willocquet et al. 2008). The estimate of pest population size is fundamental to the establishment of pest control (Anguelov, Dufourd & Yves 2017b). This chapter was written with the objective of analyzing intercropping biomass as well as the intercropping systems relationship with arthropods.

5.2. Material and methods

5.2.1. Experimental area

The experiment was carried out in Experimental Unit at EMBRAPA, located in the municipality of Lagoa Seca, Paraíba, Brazil. The cotton and cowpea cultivar used were BRS-Safira and BRS Itaim, respectively.

5.2.2. Experimental design

The experimental design used was random blocks with five arrangements that were treated with insecticide (cotton : cowpea intercropping system - t_1; cotton : cowpea intercropping system - t_2; cotton : cowpea intercropping system - t_3; sole cotton - t_4 and sole cowpea - t_5), and other five that did not receive insecticide for insect control (with the same cropping combination). Each one was replicated four times (Figure 22).

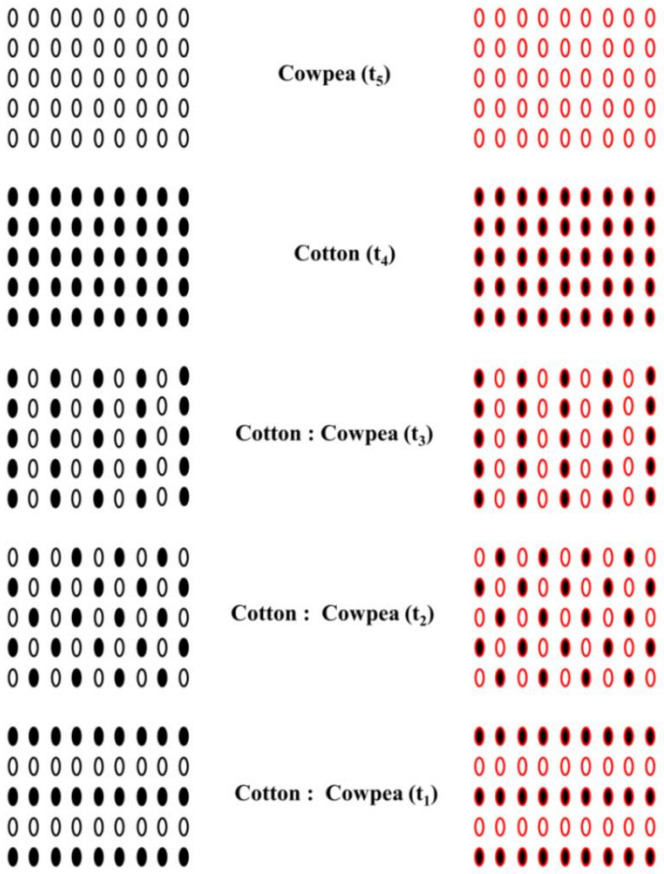

Figure 22. Experimental design of field experiments. Cotton plant (black closed circles), cowpea plant (black open circles) and insecticide treated cotton or cowpea (red circles)

The plots with chemical arrangements were treated with the insecticide thiamethoxam (ACTARA 250 WG). All plots had the same row length: 10 m. Each plot with sole cowpea or sole cotton was designed with nine rows and the spacing was 0.80 m (between rows) *x* 0.20 m (between plants).

In design for intercropping systems 1, the experimental unit was five alternated cotton and four cowpea plants. For intercropping systems 2, the experimental united was nine rows with alternated cotton and cowpea plant within the rows. For intercropping systems 3, the plot was designed with nine rows in which the columns were alternated. In all intercropping systems the spacing was 0.80 m (between rows) *x* 0.20 m (between plants).

5.2.3. Main arthropods studied, data analysis and computational models

Individual of *A. craccivora*, *A. gossypii*, *B. tabaci*, *Latrodectus geometricus* (Koch, 1841) (Arachnida: Theridiidae), *Toxomerus watsoni* (Curran, 1930) (Diptera: Syrphidae), *Chrysoperla externa* (Hagen, 1861) (Neuroptera: Chrysopodae), *Diomus seminulus* (Mulsant, 1850) (Coleoptera: Coccinellidae) and *C. sanguinea* were weekly collected on the plants of cowpea and/or cotton (sole or intercropping systems) over time. Active collection was done weekly during the sampling of arthropods, in which all captured arthropods were recorded. Different samples were maintained in alcohol (70%). They were, then, sent for identification. The number of species of pest as well as their natural enemies in cowpea and cotton were recorded on 20 plants of sole crops or in cotton-cowpea intercropping systems.

Based on literature (Tsubo, Walker & Mukhala 2001; Souza et al. 2015; Souza et al. 2017) and experimental information (number of arthropods per plot and plant productivity: standardized weight of open bolls and/or cowpea seed per line/number of plant, Singh et al. 2017), a model was proposed to explain the relationship among number of pests found within each plot (*A. gossypii*: *Ag*; *A. craccivora*: *Ac* and *B. tabaci*: *Bt*), natural enemies (*C. externa*: *Ce*; *C. sanguinea*: *Cs*; *Diomus seminulus*: *Ds; L. geometricus*: *Lg* and *T. watsoni*: *Tw*) and plant biomass (result of plant productivity over time within each plot). Simulations were done to describe the relationship among arthropods (Eqs. 5 to 12) and plant biomass (Eqs. 13 to 15).

$$Ag_{(t+1)} = Ag_{(t)}.x_1.\left(1 - \frac{Ag_{(t)}}{K_1}\right) - \left(\Delta_1 + \alpha_1 + \pi_1 + €_1 - c_1.NE_{(t)}\right) \quad (5)$$

$$Ac_{(t+1)} = Ac_{(t)}.x_2.\left(1 - \frac{Ac_{(t)}}{K_2}\right) - \left(\Delta_2 + \alpha_2 + \pi_2 + €_2 - c_2.NE_{(t)}\right) \quad (6)$$

$$Bt_{(t+1)} = Bt_{(t)}.x_3.\left(1 - \frac{Bt_{(t)}}{K_3}\right) - \left(\Delta_3 + \alpha_3 + \pi_3 + €_3 - c_3.NE_{(t)}\right) \quad (7)$$

$$Cs_{(t+1)} = Cs_{(t)}.x_4.\left(1 - \frac{Cs_{(t)}}{K_4}\right) - \left(\Delta_4 + \alpha_4 + \pi_4 + €_4 - m_1.PE_{(t)}\right) \quad (8)$$

$$Ce_{(t+1)} = Ce_{(t)}.x_5.\left(1 - \frac{Ce_{(t)}}{K_5}\right) - \left(\Delta_5 + \alpha_5 + \pi_5 + €_5 - m_2.PE_{(t)}\right) \quad (9)$$

$$Ds_{(t+1)} = Ds_{(t)}.x_6.\left(1 - \frac{Ds_{(t)}}{K_6}\right) - \left(\Delta_6 + \alpha_6 + \pi_6 + €_6 - m_3.PE_{(t)}\right) \quad (10)$$

$$Lg_{(t+1)} = Lg_{(t)}.x_7.\left(1 - \frac{Lg_{(t)}}{K_7}\right) - \left(\Delta_7 + \alpha_7 + \pi_7 + €_7 - m_4.PE_{(t)}\right) \quad (11)$$

$$Tw_{(t+1)} = Tw_{(t)}.x_8.\left(1 - \frac{Tw_{(t)}}{K_8}\right) - \left(\Delta_8 + \alpha_8 + \pi_8 + €_8 - m_5.PE_{(t)}\right) \quad (12)$$

$$Prodcow_{(t)} = YCP \quad (13)$$

$$Prodct_{(t)} = YCT \quad (14)$$

$$Prodint_{(t)} = YCP1 + YCT1 = YCPCT \quad (15)$$

In table 11, each parameter used to simulate the relationships between the arthropods pest and plant biomass or pest and natural enemies are presented. In order to simulate the populations of arthropods within each plot, it was considered that the pests can eat the plant within the plot, they can be eaten by natural enemies, reproduce, die, be born, emigrate and immigrate from each plot (Table 12, 13 and 14). For natural enemies, it was also considered that they can convert the consumed prey in natural enemy's progenies (m_x).

Table 11. Parameters used to field study simulations

Parameter	Description
K_1, K_2 and K_3	Carrying capacity of plant to receive the pests
K_4, K_5, K_6, K_7 and K_8	Carrying capacity of plant to receive the natural enemies
x_1, x_2 and x_3	Growth rate of pest population
x_4, x_5 x_6, x_7 and x_8	Growth rate of natural enemy populations
Δ_1, Δ_2 and Δ_3	Emigration rate of pest from each plot
Δ_4, Δ_5, Δ_6, Δ_7 and Δ_8	Emigration rate of natural enemies from each plot
α_1, α_2, and α_3	Immigration rate of pest in each plot
α_4, α_5, α_6, α_7, and α_8	Immigration rate of natural enemies in each plot
$€_1$, $€_2$ and $€_3$	Birth rate of pest in each plot
$€_4$, $€_5$, $€_6$, $€_7$ and $€_8$	Birth rate of natural enemies in each plot
π_1, π_2 and π_3	Death rate of pest in each plot
π_4, π_5, π_6, π_7 and π_8	Death rate of natural enemies in each plot
c_1	Rate consumption of *Aphis gossypii* by naturals enemies
c_2	Rate consumption of *Aphis craccivora* by naturals enemies
c_3	Rate consumption of *Bemisia tabaci* by naturals enemies
NE	Number of natural enemies that can feeding the pest in the plot
PE	Number of pest available in the plot
m_4, m_5, m_6, m_7, *and* m_8	Rate of pest conversion by naturals enemies
CP	Width of cowpea cropping systems
CT	Width of cotton cropping systems
YCP	Sole cowpea productivity
YCT	Sole cotton productivity
YCP1	Cowpea intercropping systems productivity
YCT1	Cotton intercropping systems productivity

K values were obtained from field experiments and represent the maximum number of each individual found within the plot. *NE* and *PE* were obtained from the sum of each *K* pests or each *K* natural enemy recorded within the plot, and other parameters were obtained from literature and attributed randomly according to type of plot and arthropod studied (Trexler, McCulloch & Travis 1988; Gotelli 2009; Levis, Maini & Petrovskii 2013). Each value of *YCP*, *YCT*, *YCP1* and *YCT1* was also obtained from field experiments and simulated over time.

The previous simulations were carried out with the software X-PEST (xpest.inra.fr). This software computes the plant biomass and loss yield caused by pests (Figure 23).

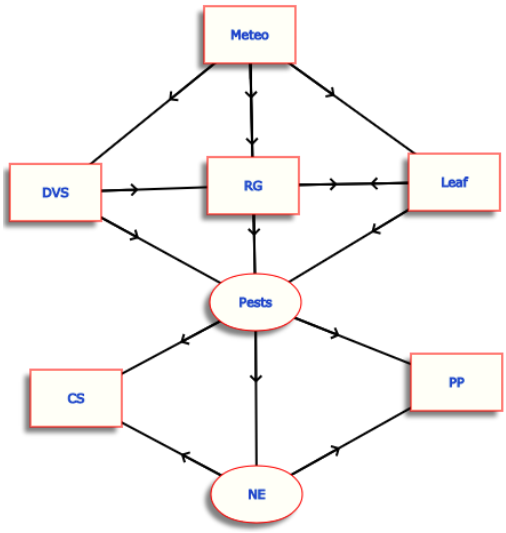

Figure 23. Platform X-PEST used in the simulations (https://xpest.inra.fr). DVS: plant development stage (Bastos et al. 2002; Willocquet et al. 2008; Assad et al. 2013); RG: cropping growth rate (Tsubo, Walker & Mukhala 2001; Milroy & Bange 2013; Cavalcante Júnior et al. 2016); Meteo: meteorology data (whether data: INMET; EMBRAPA Algodão; Gonias, Oosterhuis & Bibi 2012; Umesh, Chittapur & Jagadeesha 2017); NE: natural enemies; CS: cropping systems (sole cowpea: t_5, sole cotton: t_4, intercropping systems: t_1, t_2 and t_3); PP: plant biomass

In order to develop the model for simulations, input (Meteo: climatic variables – maximum and minimum temperature as well as radiation; DVS; RG and leaf) and output variables (plant biomass; arthropods total number: population of pest and natural enemies; arthropods control: organic or chemical and agricultural practices: sole cotton, sole cowpea and intercropping systems) were considered while making simulations. The total number of arthropods as well as the parameters used to simulate organic cropping systems of cotton and cowpea are listed in Table 12. The equations as well as the data set to simulate radiation use efficiency were used taking into account information found in literature (Tsubo, Walker & Mukhala 2001; Willocquet et al. 2008; Cavalcante Júnior et al. 2016). The input variables DVS, RG, Meteo and leaf size (Figure 22) were essential to run the program. However, results considering each one separately will not be shown here since some more experimental information is necessary to explain other relationships not measured within sole or intercropping systems of cotton and cowpea. Also, the main results shown are more relevant in comparing the relationships within the scenarios studied.

Table 12. Parameter values used to simulate the organic cropping systems in field study

Parameter	Value				
	Organic cropping systems				
	t_1	t_2	t_3	t_4	t_5
K_1	3356.00	2443.00	3132.00	4287.00	100.00
K_2	317.00	258.00	522.00	100.00	224.00
K_3	520.00	405.00	458.00	1080.00	22.00
K_4	87.00	120.00	72.00	48.00	26.00
K_5	52.00	84.00	82.00	28.00	43.00
K_6	54.00	51.00	53.00	87.0	4.00
K_7	72.00	52.00	68.00	55.00	7.00
K_8	6.00	10.00	1.00	10.00	3.00
x_1	0.15	0.15	0.15	0.15	0.15
x_2	0.14	0.14	0.14	0.14	0.14
x_3	0.12	0.12	0.12	0.12	0.12
x_4, x_5, x_6, x_7, x_8	0.60	0.60	0.60	0.60	0.60
Δ_1	0.03	0.03	0.03	0.03	0.03
Δ_2	0.04	0.04	0.04	0.04	0.04
Δ_3	0.02	0.02	0.02	0.02	0.02
$\Delta_4, \Delta_5, \Delta_6, \Delta_7$ and Δ_8	0.50	0.50	0.50	0.50	0.50
α_1	0.20	0.20	0.20	0.20	0.20
α_2	0.001	0.001	0.001	0.001	0.001
α_3	0.30	0.30	0.30	0.30	0.30
$\alpha_4, \alpha_5, \alpha_6, \alpha_7$ and α_8	0.30	0.30	0.30	0.30	0.30
ϵ_1, ϵ_2 and ϵ_3	0.50	0.50	0.50	0.50	0.50
$\epsilon_4, \epsilon_5, \epsilon_6, \epsilon_7$ and ϵ_8	0.50	0.50	0.50	0.50	0.50
π_1, π_2 and π_3	0.50	0.50	0.50	0.50	0.50
$\pi_4, \pi_5, \pi_6, \pi_7$ and π_8	0.50	0.50	0.50	0.50	0.50
c_1	0.13	0.13	0.13	0.13	0.13
c_2	0.12	0.12	0.12	0.12	0.12
c_3	0.20	0.20	0.20	0.20	0.20
NE	271.00	317.00	276.00	224.00	180.00
PE	4193.00	3106.00	4112.00	5388.00	346.00

The parameter values of cropping productivity as well as the total number of pest and natural enemies used for simulation in chemical cropping systems are listed in Table 13.

Table 13. Parameter values used to simulations of chemical cropping systems in field study

Parameter	Value				
	Chemical cropping systems				
	t_1	t_2	t_3	t_4	t_5
K_1	959.00	868.00	1071.00	3728.00	100.00
K_2	288.00	297.00	230.00	100.00	297.00
K_3	837.00	506.00	638.00	684.00	35.00
K_4	47.00	12.00	26.00	38.00	26.00
K_5	61.00	18.00	50.00	39.00	40.00
K_6	10.00	4.00	28.00	8.00	-
K_7	63.00	55.00	46.00	45.00	-
K_8	6.00	4.00	4.00	3.00	-
x_1	0.15	0.15	0.15	0.15	0.15
x_2	0.14	0.14	0.14	0.14	0.14
x_3	0.12	0.12	0.12	0.12	0.12
x_4, x_5, x_6, x_7, x_8	0.60	0.60	0.60	0.60	0.60
Δ_1	0.003	0.003	0.003	0.003	0.003
Δ_2	0.004	0.004	0.004	0.004	0.004
Δ_3	0.002	0.002	0.002	0.002	0.002
$\Delta_4, \Delta_5, \Delta_6, \Delta_7$ and Δ_8	0.30	0.30	0.30	0.30	0.30
α_1	0.60	0.60	0.60	0.60	0.60
α_2	0.004	0.004	0.004	0.004	0.004
α_3	0.50	0.50	0.50	0.50	0.50
$\alpha_4, \alpha_5, \alpha_6, \alpha_7$ and α_8	0.40	0.40	0.40	0.40	0.40
ϵ_1, ϵ_2 and ϵ_3	0.30	0.30	0.30	0.30	0.30
$\epsilon_4, \epsilon_5, \epsilon_6, \epsilon_7$ and ϵ_8	0.30	0.30	0.30	0.30	0.30
π_1, π_2 and π_3	0.70	0.70	0.70	0.70	0.70
$\pi_4, \pi_5, \pi_6, \pi_7$ and π_8	0.70	0.70	0.70	0.70	0.70
c_1	0.13	0.13	0.13	0.13	0.13
c_2	0.12	0.12	0.12	0.12	0.12
c_3	0.20	0.20	0.20	0.20	0.20
NE	187	93	154	133	78
PE	2084	1671	1939	4512	332

5.3. Results and discussion

The result is possibly a combined influence from abiotic and biotic factors with the experimental treatment in organic and chemical systems (Figure 24 to 28). Comparing A and B figures, it is possible to find some relevant quantitative and qualitative differences expressed by different population sizes and line trajectories. Regarding the intercropping systems t_1 (organic control), it was observed an asymptotic growth population with predator and prey species reaching stability after at least twenty-time steps (Figure 24A). In intercropping t_1 (chemical control) the same behavior was observed in natural enemy species, except for *T. watsoni* that tended to be less abundant than other natural enemies, with temporal dynamics characterized by instability of population and limit cycle in two points over the time (Figure 24B).

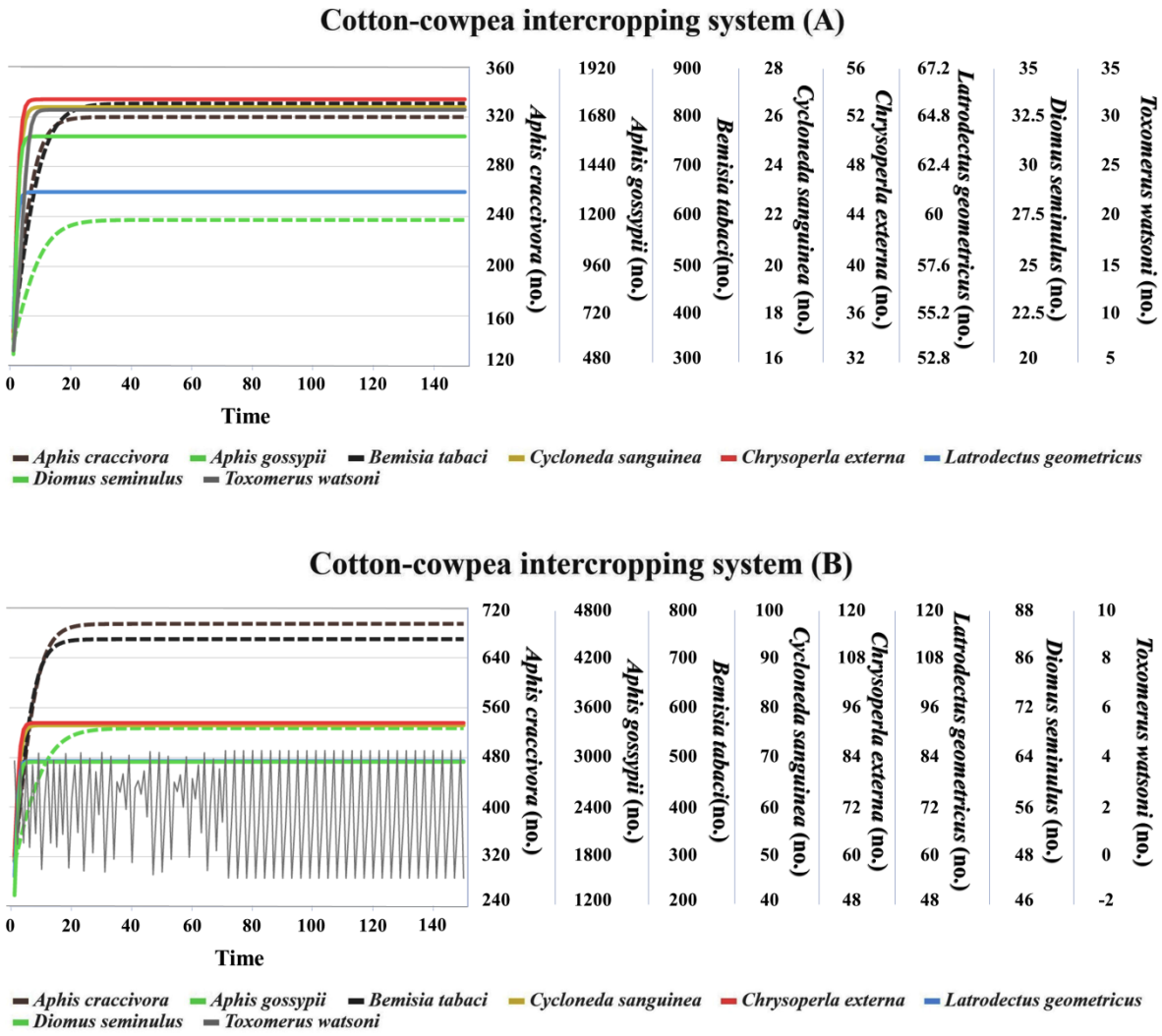

Figure 24. Relationship among arthropods (pests: short dash lines; natural enemies: solid lines) studied in cotton-cowpea intercropping systems t_1 (organic cropping system: A, and

chemical cropping system: B). Each y axis is an individual scale representing the number of consumed pest as well as their natural enemies number over time. Lagoa Seca-PB: 2015

Taking into account biotic and abiotic factors previously described (Figure 23), it was simulated that in intercropping systems t_2 (organic or chemical control), due to the arrangements (plant of cotton and plant of cowpea within the same row), there was just stability of temporal dynamics for the individuals studied (Figure 25A and B).

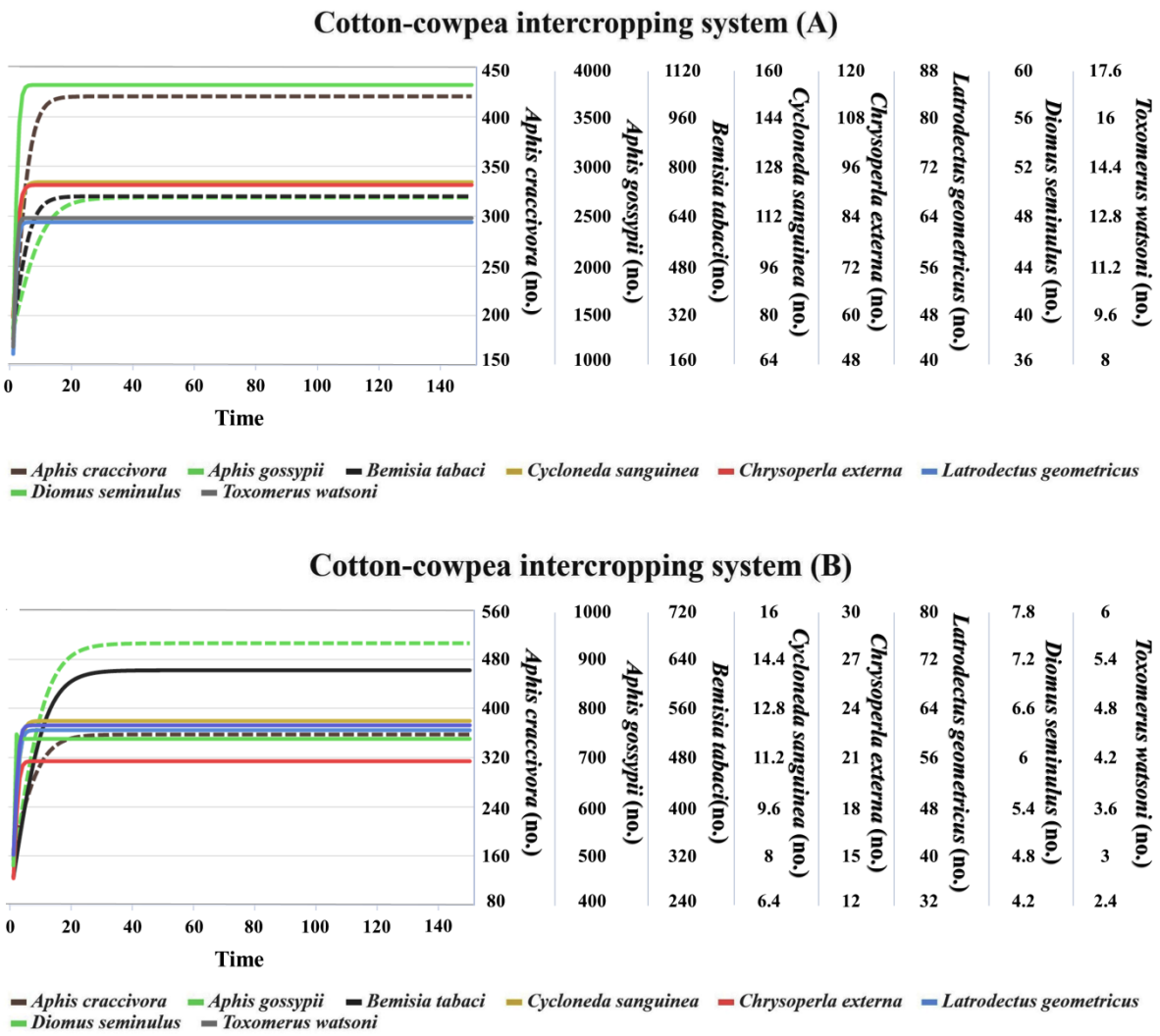

Figure 25. Relationship among arthropods (pests: short dash lines; natural enemies: solid lines) studied in cotton- cowpea intercropping systems t_2 (organic cropping system: A, and chemical cropping system: B). Each y axis is an individual scale representing the number of consumed pest as well as their natural enemies number over time. Lagoa Seca-PB: 2015

Simulations used to predict the relationship of pest and natural enemies in intercropping systems t_3 (organic or chemical control), show that due to cropping systems arrangement

(row of cotton alternates with row of cowpea) and number of pests, the temporal dynamics of *C. sanguinea*, *C. externa*, *D. seminulus*, *L. geometricus* and *T. watsoni* were also stable (Figure 26A and B). Only population sizes were different between organic and chemical systems.

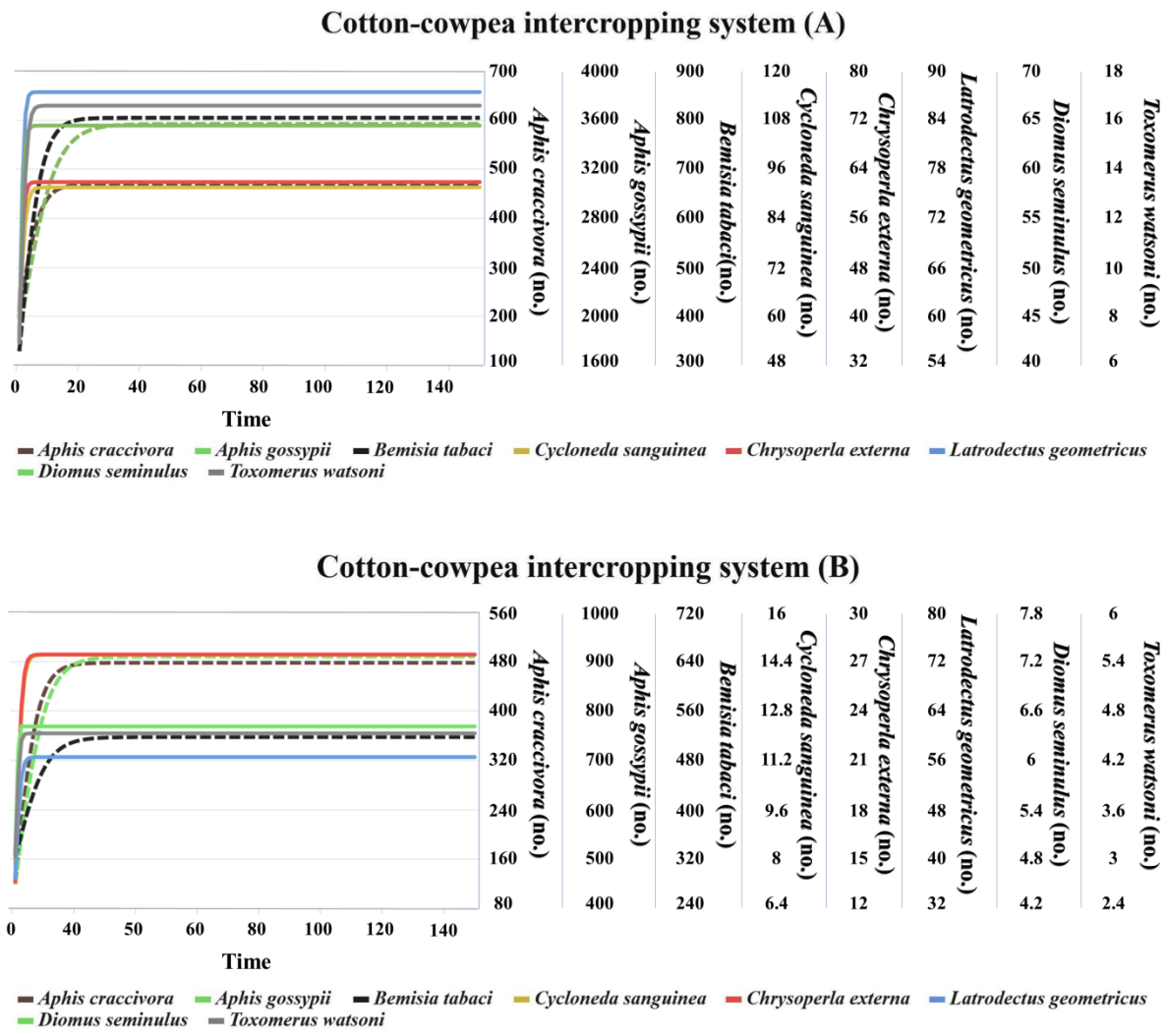

Figure 26. Relationship among arthropods (pests: short dash lines; natural enemies: solid lines) studied in cotton- cowpea intercropping systems t_3 (organic cropping system: A, and chemical cropping system: B). Each y axis is an individual scale representing the number of consumed pest as well as their natural enemies number over time. Lagoa Seca-PB: 2015

In sole cotton ($t_{4\ (organic\ control)}$), the temporal dynamics of *T. watsoni* were unstable. Nevertheless, the temporal dynamics of other natural enemies were stable within the plot (Figure 27A). Regarding the simulations to sole cotton $t_{4\ (chemical\ control)}$, it was observed that the temporal dynamics of *C. sanguinea*, *C. externa* and *L. geometricus* were stabilized at the same time of the temporal dynamics of pests. On the other hand, in the same chemical

arrangement, it was predicted that initial oscillations, and then stability, tends to occur in temporal dynamics of *T. watsoni* and *D. seminulus*, while temporal dynamics of other arthropods are stable (Figure 27B).

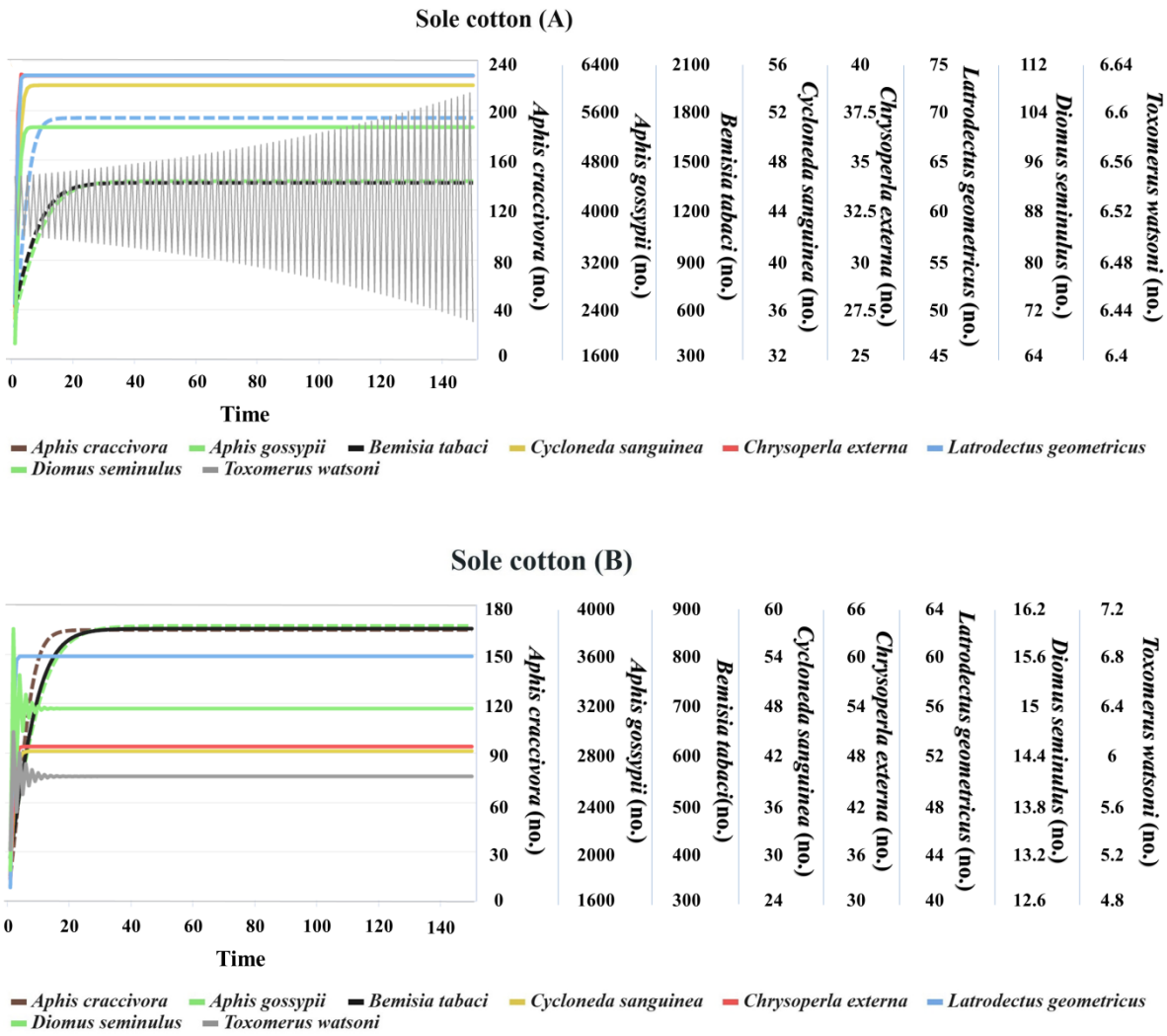

Figure 27. Relationship among arthropods (pests: short dash lines; natural enemies: solid lines) studied in sole cotton t_4 (organic cropping system: A, and chemical cropping system: B). Each y axis is an individual scale representing the number of consumed pest as well as their natural enemies number over time. Lagoa Seca-PB: 2015

Simulations to analyze sole cowpea $t_{5\ (\text{organic or chemical control})}$, indicated that *T. watsoni* cannot occur within the plot. Temporal dynamics of *L. geometricus* and *C. externa* were stable. On the other hand, it was noticed that the population size of *C. sanguinea* was smaller within chemical sole cowpea, while in organic sole cowpea decreases of individual numbers occurred, being its temporal dynamics characterized by stability (Figure 28A). It was also

predicted that the temporal dynamics of other natural enemies can be stable in chemical control of sole cowpea (t_5: Figure 28B).

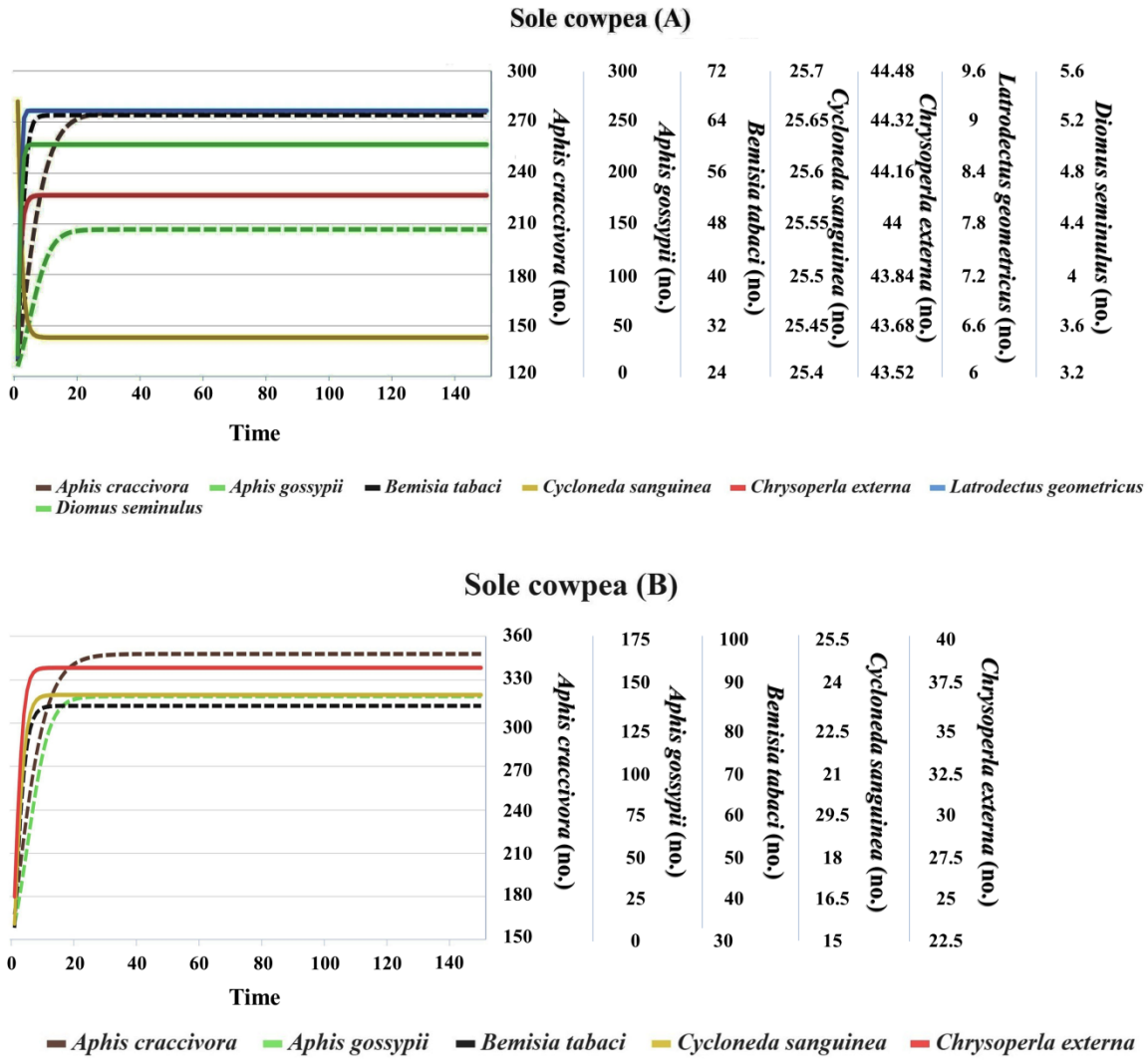

Figure 28. Relationship among arthropods (pests: short dash lines; natural enemies: solid lines) studied in sole cowpea t_5 (organic cropping system: A, and chemical cropping system: B). Each y axis is an individual scale representing the number of consumed pest as well as their natural enemies number over time. Lagoa Seca-PB: 2015

It was found that, in general, the abundance of natural enemies within each plot was dependent on arrangement of plants. In organic control of intercropping systems t_2 (Figure 25A) and t_3 (Figure 26A), the number and diversity of natural enemies was higher than in sole cowpea (Figure 28A). These results are useful because these arthropods can serve as agents regulating pest species behavior and plant choice in agroecosystem (Golan et al. 2017). These characteristics in some companion plants were also fundamental to the attraction of natural

enemies providing shelter in order to improve biological pest control (Ben-Issa, Gomez & Gautier 2017).

Simulations suggested that the intercropping system t_1 (chemical control) changes the stability in *T. watsoni* populations. There are different factors capable of influencing stability in insects (Zhao et al. 2015). Among them, with limitation of food, competition with other natural enemies can influence species in response to higher probability of dying (Reis Jr, Souza & Vilela 2000; Roubinet et al. 2017). On the other hand, the same can occur to the species in sole cotton (t_4: organic control). The results obtained here indicated that the stability or instability can occur due to repulsion or mortality of arthropods occasioned by chemical products or specific plant response that can be based on availability of free amino acids, phenol content as well as protein concentration (Golan et al. 2017). These substance profile can be different among host plant species and varieties that can protect themselves from pest attraction, either in absence of chemical substances or morphological structures that can affect some biological parameters as life cycle, reproduction, and population dynamics of the pest (Amin et al. 2017).

Simulations applied to study the cropping systems that received insecticide to pest control, especially in sole cowpea, also showed that the diversity and abundance of natural enemies can be smaller than in other cropping systems. This result was somewhat expected because availability of prey and the presence of beneficial insects are generally influenced by toxic effects of insecticides and availability of pest (Heimoana et al. 2017). On the other hand, due to the ability of some species, a movement across the land in order to choose the best habitat to make progeny, according to their traits association and physiological tolerance, may occur (Young et al. 2017).

Using any system with higher radiation use efficiency and reducing the risk of loss crop productivity due to some abiotic factors, diseases, weeds and pests, may be beneficial to plant biomass (Tsubo, Walker & Mukhala 2001; Gao et al. 2010; Assad et al. 2013). In fact, this could occur while regarding the simulations to compare the relationship between radiations use efficiency and crop productivity in the organic plots. In these cropping systems it was expected that, if the population of *A. gossypii*, *A. craccivora* and *B. tabaci* were stabilized by biotic (many natural enemies) and abiotic (climatic) factors, a higher biomass production would be observed in intercropping system t_1 (2828.41 g/row, RUE: 4, Figure 29A), intercropping system t_2 (2485 g/row, RUE: 4, Figure 29B) and intercropping system t_3 (2409.86 g/row, RUE: 4, Figure 29C). These results indicate that higher radiation to intercropping systems of cotton and cowpea was an important factor to regulate the plants,

and consequently, their herbivorous behavior. In general, it is believed that this result could be useful to farmers because it can provide higher gross monetary return and contribute to pest reduction over the seasons. Other important results showing stability of intercropping systems were also discussed by Raseduzzaman & Jensen (2017) and Bijan et al. (2017). Results found by Singh et al. (2017) agree with the results found here, who observed that intercropped plots recorded higher productivity, and consequently, higher gross monetary returns to the farmer.

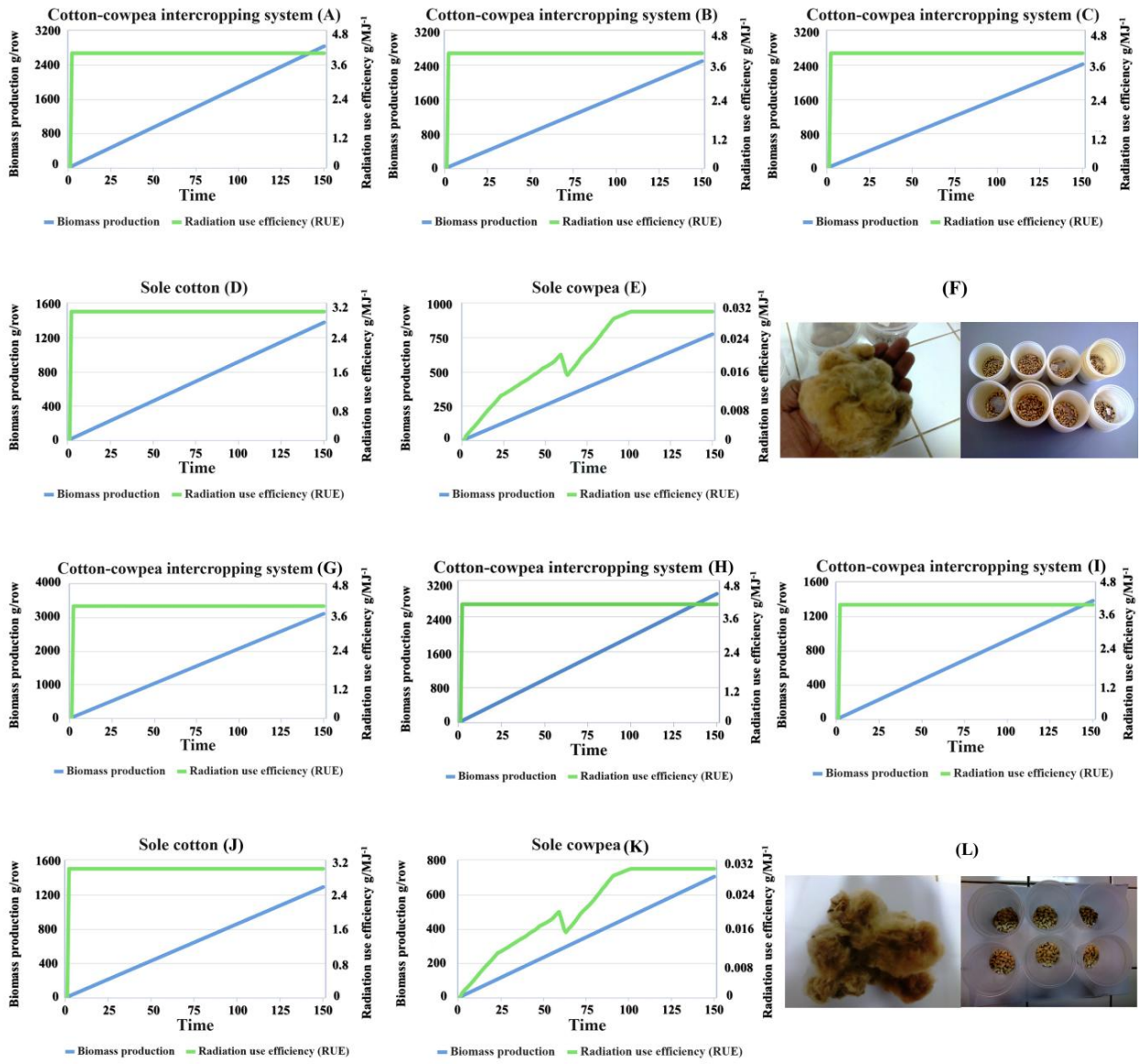

Figure 29. Relationship among radiation use efficiency (RUE) and biomass production organic control (A-F) and chemical control (G-L). Intercropping system t_1 (A and G), intercropping system t_2 (B and H), intercropping system t_3 (C and I), sole cotton t_4 (D and J), sole cowpea t_5 (E and K) and open bolls (left) and cowpea seeds (right), (F and L). Lagoa Seca-PB: 2015

Radiation use efficiency range according to cropping practices and its incidence decrease in an area where there are less favorable conditions (Willocquet et al. 2008). The type of cropping combinations can bring advantages or provide negative impact to agroecosystem (Htet, Soomro & Bo 2017). Here it was found that biomass production was higher in intercropping system t_1 (3106.23 g/row, RUE: 4, Figure 29G), intercropping system t_2 (2903.09 g/row, RUE: 4, Figure 29H) than in sole cowpea (704.14 g/row, RUE: 0.03, Figure 29K) or sole cotton (1287.00 g/row, RUE: 3, Figure 29J). This result was important to understand that more biomass can also be produced within intercropped chemical plots.

Simulations to evaluate cropping biomass production indicate that the best cropping arrangements were the cotton-cowpea intercropping systems (t_1 and t_2, Figure 29A, B, G and H). The findings confirmed our hypothesis that crop arrangement can affect positive aspects of the productivity and biomass production, and it may occur due to the plant distribution within the plot that probably provided similar incidence of radiation as well as nutrients due to the proximity between cotton and cowpea plants. On the other hand, it may not have occurred in intercropping systems t_3 because the plant distribution was different within the plot (Figure 22). These results are interesting because some cowpea-cotton intercropping systems can offer higher value of seed, land equivalent, and maximum biomass production (Randhawa 2017; Singh et al. 2017). Regarding the biomass, the results found in intercropping systems agree with the simulations carried out by Htet, Soomro & Bo (2017), who explained that, in general, intercropping systems are more efficient than sole cropping systems since they improve the efficient use of resources as well as land intensification due to improvement in overall yield, nutrients and soil fertility (Hassen et al. 2017; Umesh, Chittapur & Jagadeesha 2017).

5.4. Conclusions

Simulations using the platform X-PEST were useful to predict relationships among the main pest, natural enemies and biomass production in sole cotton, sole cowpea and cotton-cowpea intercropping systems. Computational simulations confirmed that the biomass production was higher in some cotton-cowpea intercropped than in sole cropping systems. The results found here can be used as a tool to predict optimal cropping systems vising implementation of any integrated pest management in the field conditions.

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6. CONCLUDING REMARKS

After considering all results we can extract the following conclusions:

- The results of this study suggest that cotton-cowpea intercropping can significantly impact pest and natural enemies.
- The results found in the current study can be useful to predict relationships among arthropods in greenhouse or field condition.
- The design proposed in this study makes possible to know how to optimize plant productivity and also to investigate biomass production and radiation.
- Sensitivity analysis was important to show parameters with potential to make significant changes in aphids' dynamics.
- *Cycloneda sanguinea* was capable of reproducing over successive generations, establishing its progeny in a specific arrangement within a habitat protected by a cage. These results can be useful to indicate to the grower what the right time to release the predator in cropping systems.
- The platform X-PEST was useful to make important predictions giving support to decision-making in crop protection.
- The results obtained from amino acid profile highlights the importance of also to investigate the amino acid profile from other parts of plants.
- The use of cultural control as well as biological and chemical control by selective insecticide was successful in the current study.