

**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**

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

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DEDICATION

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

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EPIGRAPH

*«L'Éternel est mon berger:
Je ne manquerai de rien».*

Psaumes 23:1

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 abundância 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; Wongsu 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-Żytka 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.

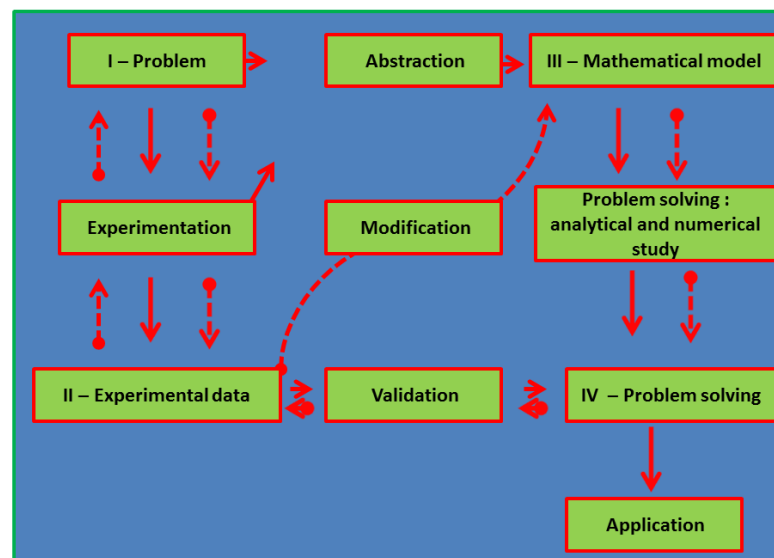


Figure 1. Step necessary to construct a model. Modified from Bassanezi (2013)

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-	Yes					Loison et al. 2017
CROPGRO						
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-					Yes	Papanikolaou et al. 2016
DeAngelis						
Hassell-Varley					Yes	Papanikolaou et al. 2016
Lotka and Voltera					Yes	Hadziabdić, 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, Honěk & 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 (°C) 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 (°C) 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

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 STUDY¹

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

¹ Chapter published in Annals of the Brazilian Academy of Sciences

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

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

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.