Arthropod-Plant Interactions (2014) 8:461–468
DOI 10.1007/s11829-014-9320-5

ORIGINAL PAPER

Reproductive performance of striped mealybug *Ferrisia virgata* Cockerell (Hemiptera: Pseudococcidae) on water-stressed cotton plants subjected to nitrogen fertilization

Martin D. Oliveira · Paulo R. R. Barbosa · Christian S. A. Silva-Torres · Rodrigo R. Silva · Eduardo M. Barros · Jorge B. Torres

Received: 31 January 2014 / Accepted: 13 July 2014 / Published online: 25 July 2014
© Springer Science+Business Media Dordrecht 2014

Abstract Sap-sucking sessile insects depend on their selected host plant for their development; hence, they are influenced by the nutritional quality of the plant, especially the available nitrogen (N) and water content in the plants. The levels of N in the plant sap can vary as function of the N fertilization applied to enhance crop yield, while deficit of water takes place during drought periods. The performance of the striped mealybug on cotton plants subjected to N fertilization and water stress (=deficit of water) was evaluated. Potted cotton plants grown in a greenhouse were subjected to N fertilization and two irrigation regimes considering regular irrigation and water stress. Cotton plants were infested with 150 newly hatched nymphs. The survival was measured as the percentage of mealybugs alive 25 days after infestation. The biological traits of duration of development + the pre-reproductive period, and the number and sex ratio of the offspring were determined. The survival of nymphs was similar across all treatments and averaged 38 %. Likewise, the developmental times were similar across treatments averaging 47 days, with 84 % of female offspring. However, offspring production was nearly twofold higher for water-stressed plants with successive N fertilizations. Offspring production was increased by 37 % as a function of water stress, and by 18 % as a function of N fertilization. Therefore, we conclude that the striped mealybug performance is enhanced on cotton plants under N fertilization and water stress. Based on the results, proper fertilization and irrigation management relieving plant from stress can be helpful in avoiding generalized infestations of striped mealybug on cotton.

Keywords Herbivory · Pseudococcidae · *Ferrisia virgata* · Soil moisture

Handling Editor: Joseph Dickens.

M. D. Oliveira · P. R. R. Barbosa · C. S. A. Silva-Torres · R. R. Silva · E. M. Barros · J. B. Torres (✉)
Departamento de Agronomia, Entomologia, Universidade Federal Rural de Pernambuco, Rua Dom Manoel de Medeiros s/n, Dois Irmãos, Recife, Pernambuco 52171-900, Brazil
e-mail: jtorres@depa.ufrpe.br

M. D. Oliveira
e-mail: martindo@uol.com.br

P. R. R. Barbosa
e-mail: prrbagro@yahoo.com.br

C. S. A. Silva-Torres
e-mail: christian@depa.ufrpe.br

R. R. Silva
e-mail: rodrigo@depa.ufrpe.br

E. M. Barros
e-mail: embcarneiro@hotmail.com

Introduction

The performance of sap-sucking insects such as mealybugs can be influenced by the content of the phloem sap of the host plants (Larsson 1989). Among other nutrients in the phloem sap, free amino acids are the most important source of protein for phloem feeders (Panizzi and Parra 1991). Thus, the amount of nitrogen in a plant influences the insect performance (Miles et al. 1982; Jansson et al. 1991; Jiao et al. 2012). The N content in the plant can vary as a function of N availability in the soil, where the plants are grown and augmented via addition by fertilizations, while its absorption is influenced by the balance of water availability in the plant and in the soil.

The use of fertilization, especially with N, is a common agronomic practice to maximize yield and quality of products such as the cotton fiber (Jadoskil et al. 2010). Nevertheless, incorrect application of fertilizers, including excessive dosages of N, may result in variable levels of free amino acids in the plant, which may in turn favor the occurrence of herbivores. Research data show that fertilization resulting in high concentration of N in the plant promote better performance of chewing insects such as the beet armyworm *Spodoptera exigua* (Hübner) (Lepidoptera: Noctuidae) on cotton plants (Chen et al. 2008) and the red postman butterfly *Heliconius etaro phyllis* (Fabr.) (Lepdoptera: Nymphalidae) on passion flower (Kerpel et al. 2006). Furthermore, N fertilization positively enhances the performance of sap-sucking insects such as the mealybugs *Planococcus citri* (Risso) (Hemiptera: Pseudococcidae) on cocoa and coleus plants (Fennah 1959; Hogendorp et al. 2006), *Saccharicoccus sacchari* (Cockerell) on sugarcane (Rae and Jones 1992), planthoppers *Prokelisia dolus* Wilson and *P. marginata* (Van Duzee) (Hemiptera: Delphacidae) on saltmarsh cordgrass (Huberty and Denno 2006), and aphids such as *Aphis gossypii* Glover (Hemiptera: Aphididae) on cotton (Barros et al. 2007), *Rhopalosiphum padi* (L.), and *Sitobion avenae* (Fabr.) on wheat (Aqueel and Leather 2011).

Besides correct fertilization, appropriate water supply plays a key role in plant nutrient uptake and in subsequent distribution of nutrients throughout the plant. Under dryland cotton farming, the plants can be subjected to water stress because of temporary periods of insufficient rain, especially in the semiarid areas. Further, according to Miles et al. (1982), plants under water stress can reduce moisture in the plant tissues, starch, and carbohydrates in the leaves, and mainly, soluble nitrogen and sugars. Furthermore, increased densities for some insect species have been reported on water-stressed plants. According to White (1969), outbreaks of the psyllid *Cardiaspina densitexta* Taylor on eucalyptus in Australia were due to a previous deficit of water, supporting the plant-stress hypothesis (PSH) proposed by the same author. Moreover, greater densities of the aphid *Diuraphis noxia* (Mordvilko) on wheat (Archer et al. 1995) and of the leafminer fly *Phytomyza conyzae* Hendel (Diptera: Agromyzidae) on cadowydd (Staley et al. 2006) have been reported for water-stressed plants. In addition, results with plants subjected to water stress have shown enhanced performance of the aphids *Myzus persicae* (Sulz.) and *Brevicoryne brassicae* (L.) on oilseed rape (Miles et al. 1982) and the mealybug *Phenacoccus herreni* Cox & Williams on cassava (Calatayud et al. 2002).

Enhanced performance of some insects on water-stressed plants is related to improved quality of the plant to the herbivores, corroborating with the PSH proposed by White (1969). The enhanced performance of the herbivorous insects on water-stressed plants is related to improved nutritional quality of the host plant. However, it is overcome by other morphological and physiological changes, which also occur on plants under water stress. For instance, the reduction in turgor pressure and the amount of water content in the plant (Hsiao 1973; Inbar et al. 2001; Huberty and Denno 2004) increase in allelochemicals (Gershenzon 1984; Mattson and Haack 1987; Inbar et al. 2001) and reduction in plant development (Price and Clancy 1986; Price 1991). Nevertheless, according to Huberty and Denno (2004), plants submitted to water stress negatively affect the performance of sap-sucking insects, while the chewing insects are not affected. Therefore, this subject is an open avenue for research to better understand the response of insect pests to cultivated plants, and the outcome can be species specific.

Infestations of mealybugs including the cotton mealybug *Phenacoccus solenopsis* Tinsley and the striped mealybug *Ferrisia virgata* Cockerell (Hemiptera: Psdeudococcidae) on cotton plants have been reported for different areas of Brazil, which is the fourth largest cotton producer in the world (Bastos et al. 2007; Ferreira et al. 2009; Miranda et al. 2011). The striped mealybug was reported recently infesting cotton fields in the semiarid area of Pernambuco state (Torres et al. 2011) and exhibited high performance with nearly 412-fold population growth on cotton (Oliveira et al. 2014). This new arrival has worried growers and integrated pest management practitioners due to lack of information about the pest and certified practices to restrain the pest population growth either using chemical or biorational methods.

Most area of cotton cultivation in Brazil is rain fed, where areas utilized for seed production are irrigated during the dry season. In the semiarid region the rainfall is irregular, with plants often been submitted to water stress during their development, what also can take place in the Cerrado, the region with largest area of cotton in Brazil, for short periods of time during the summer rainy season. Further, cotton cultivated in these regions by small and large scale producers occasionally occurs under N fertilization for increased yield. Therefore, knowledge of how the striped mealybug respond to cotton plants subjected to water tress and nitrogen fertilization will provide understanding of the potential of this species as a cotton pest in Brazil, especially in the fields located in the semiarid areas. Thus, the objective of this work was to evaluate the development and reproduction of *F. virgata* fed cotton plants fertilized with nitrogen and subjected or not subjected to water stress.

Materials and methods

Experimental conditions

The studies were conducted in the Laboratory of Insect Ecology and in the Experimental Area of the Crop

Protection Unit of the "Universidade Federal Rural de Pernambuco" (UFRPE), Recife, Pernambuco State. Cotton plants were cultivated in a greenhouse (6 m long × 2.5 m high × 2 m wide) under environmental conditions of temperature (average: 26.6 °C; range 19.7–37.2 °C), relative humidity (average: 69.0 %; range 34.6–93.8 %), and photophase (12:12 h) monitored by the DataLogger Hobo® (Onset Computer, Bourne, MA, USA), which was regulated to register the conditions at 30-min intervals.

Experimental design

Cotton plants (*Gossypium hirsutum* L.) of cultivar CNPA 7H were cultivated in pots of 10-L volume filled with a standard mixture of clay soil, sand, and humus (2:1:1) plus 10 g of phosphorus and 10 g of potassium fertilizers (Yara Brasil Fertilizantes S.A., Porto Alegre, RS, Brazil), while the N was subsequently applied as supplementary fertilization to vary its amount in the plant. Then, 56 plants aged 20 days (~5 expanded leaves) and exhibiting roughly the same height were selected. These plants were divided into two groups: 28 plants were maintained only with the fertilization at planting date, whereas the other 28 plants received fertilization at planting date and subsequent N fertilizations. Nitrogen fertilization was applied 20, 30, 40, 50, 60, and 70 days after plant emergence. The subsequent N fertilizations after plant emergence were performed by applying 40 mL/pot of the dilution made with 10 g/L of ammonium sulfate [$(NH4)_2SO_4$; 20 % N]. Thus, we considered the 28 cotton plants cultivated without supplementary nitrogen fertilization (−N) and the 28 cotton plants cultivated with six supplementary nitrogen fertilizations (+N).

At 30 days after plant emergence, the plants belonging to the +N and −N treatments were subjected to two factors regarding the irrigation regimes. Two water regime supplies were determined based on previous measurements taken under the plant cultivation condition. The two water regimes were chosen to obtain plants that were visually with permanent turgid leaves, as well as plants that were with partial wilting leaves. In plants cultivated under regular irrigation, the soil water potential averaged 0.5 PSI, while, in under water stress, had soil water potential of 0.01 PSI; these soil water potentials were determined using analogical tensiometers (SondaTerra® Equipamentos Agronômicos, Piracicaba, SP). Water was supplied via a drench over the soil near the plant base, daily between 8 a.m. and 10 a.m. Therefore, after setting the irrigation regimes, four treatments were set up, combining N fertilization (+N and −N) under two regimes of irrigation [plants with (−W) and without water (+W) stress]. Thus, 14 plants of the +N treatment and 14 plants of the −N treatment were irrigated daily with 600–800 mL of water per plant (hereafter, "plants without water stress"), and the other 14 plants of the same treatments were irrigated with 100–300 mL/plant (hereafter, "water-stressed plants").

Performance measures of *F. virgata*-fed cotton plants under variable nitrogen fertilization and water supply

Cotton plants (aged 40 days) maintained under the four conditions [+N and under water stress (−W), +N and without water stress (+W), −N and −W plants, and −N and +W plants] were infested with newly hatched *F. virgata* nymphs (aged <12 h). These nymphs were collected from the stock colony of *F. virgata* reared on pumpkin *Cucurbita moschata* (Duch.) Duch. Ex Poir cultivar Jacarezinho. To collect the nymphs from infested pumpkins, leaf discs of 4.8-cm diameter were obtained from cotton leaves harvested from the median section of plants of each treatment. These leaf discs were laid over a pumpkin infested with adult females of *F. virgata*, allowing the neonate nymphs (i.e., crawlers) to move to the discs. After 15 min, the leaf discs were removed from the pumpkins and placed on Petri dishes (9-cm diameter) and closed with polyvinyl chloride (PVC) plastic film (Alpfilm, São Paulo, SP, Brazil). The number of neonate nymphs was calculated as 150 nymphs/leaf disc by adding or removing neonate nymphs, if necessary, using a fine paint brush (No. 0) under a stereomicroscope (Opton™–NTB 3A). The transfer of infested-leaf discs to the cotton plant in the greenhouse was performed by attaching the leaf discs with an iron clip to the upper expanded leaves, being one leaf disc per leaf and two leaf discs per plant. The petiole of the respective infested leaf received entomological glue (Bio-Stop Cola®, Biocontrole S.A., São Paulo, SP, Brazil) to avoid nymphs escaping from the releasing site. In addition, the main stem of the plant was smeared with entomological glue to prevent other insects from climbing on cotton plants.

The experimental design consisted of 2 × 2 factorial with two treatments (+N and −N) under two irrigation regimes (+W and −W) with 14 replications each. The data for survival of mealybugs, duration of development + pre-oviposition periods, and the number of offspring produced were averaged per plant considering the results obtained from two leaves as subsamples per plant. The percentage of survival consisted of the number of mealybugs found per leaf 25 days after infestation as a function of the initial release density of 150 neonate nymphs/leaf. After this evaluation, two adult females were transferred to upper leaves on the same plant. The petiole of the newly infested leaves with adult females was smeared with entomological glue to prevent females from escaping. For these females, we recorded the age of initial offspring production and the number of offspring produced during 16 consecutive days of evaluation. According to Oliveira et al. (2013), the striped mealybug under the studied conditions molted to adult within approximately 25 days after infestation and exhibited reproductive period of about 16 days. Furthermore, a period longer than 16 days could also affect the results due to cotton leaf senescence. Thus, the average of development and pre-oviposition periods, adult sex ratio, and the number of offspring produced during 16 days were recorded for females confined to the plants.

The offspring sex ratio of *F. virgata* female raised feeding cotton plants under N fertilization and irrigation regimes was investigated. To do so, 128 s-instar nymphs were randomly collected from eight plants (16 nymphs per female) from each treatment. These nymphs were transferred to cotton leaf discs harvested from the same plant and placed into Petri dishes at rate of 25 nymphs per disc and considered as one replications. The nymphs were kept under 26 °C in the laboratory, which was the average temperature in the greenhouse where they were previously raised. The sex ratio of nymphs was determined when male nymphs molted to the third-instar nymph. Male nymphs exhibit defined head, slender body, and denser wax layer over the body as compared to the females in the third-instar.

The role of the N fertilization and irrigation regimes on the development of cotton plants and on the nutrient contents in the leaves of these plant was also evaluated. Five days after applying the fourth N fertilization (plant age: 55 days) leaves from the median section of the plants (determined by the number of nodes in the main stem) were harvested from four plants of each treatment (three leaves/plant). The collected leaves ($n = 12$ leaves per treatment) were placed in plastic bags, identified, and conducted to the laboratory to run foliar analysis regarding the nutrient contents (LabFert—Laboratório de Análises Agrícolas Ltda, Recife, PE, Brazil). The analysis was performed using the methodology of Orlando Filho and Zambello Jr (1983). In addition, the development of the plants 123 days old and subjected to the treatments (+N and −N) and treatment factors (+W and −W) was evaluated using ten plants (replication) per N fertilization and irrigation regime. The evaluation step consisted of determining the fresh weight of the whole plant, dry weight, and the number of bolls produced per plant. To obtain the dry weight, the plants were sliced into small parts, placed into paper bags, and then dried using a forced-air oven regulated at 54 °C for 72 h.

Data analyses

The results on survival, developmental times, offspring sex ratio, reproduction of mealybugs, and development response of plants submitted to the treatments were tested for normality (Kolmogorov–Smirnov's test) and homogeneity (Bartlett's test) of variance using the Proc Univariate and Proc analysis of variance (ANOVA) of SAS, respectively (SAS Institute 2001) and transformed, if necessary. Untransformed results are presented in tables and figures. Furthermore, the percentage of mealybug survival determined at 25 days after infestation, the development + pre-oviposition duration, the number of offspring produced, sex ratio, the fresh and dry weight of plants, and the number of bolls produced per plants were subjected to two-way ANOVA (N fertilization and irrigation regimes) using PROC ANOVA of SAS (SAS Institute 2001). The mean comparisons were performed using Fisher's test ($df = 1$) of ANOVA with 0.05 significance levels. The data of leaf nutrients were transformed into percentage for each nutrient evaluated as a function of nutrient total and compared using pair-wise chi-square test after the null hypothesis of equality was rejected at 0.05 significance levels by PROC FREQ of SAS (SAS Institute 2001).

Results

The leaves of cotton plants submitted to N fertilization and irrigation regimes showed variation in the nutrient content (Table 1). A significant increase of the N content was observed in the leaves of plants receiving successive N fertilizations and water stress over those not receiving N supplements regardless of water levels. On the other hand, +N and +W plants and −N and −W plants exhibited similar amounts of nitrogen content in the leaves ($\chi^2 = 0.11$, $P = 0.7360$). Leaves of +N and −W plants exhibited twofold greater N content than leaves of −N and −W plants ($\chi^2 = 7.85$, $P = 0.0051$).

Plant development and boll production varied as function of N fertilization and irrigation regimes (Table 2). −W plants, irrespective of N fertilization (both +N and −N), exhibited greater weights (fresh and dry) and number of bolls (Table 2). The overall results show that plant weight and boll production were twofold and fourfold greater, respectively, for plants under N treatment without water stress as compared to plants with water stress (Table 2).

The survival of mealybug nymphs evaluated 25 days after infestation, the development + pre-oviposition duration, and the sex ratio of the offspring produced were similar across the treatments studied (+N and −N, +W and −W) (Table 3). The overall mean percentage (±SE) across all treatments for nymphal survival evaluated 25 days after infestation was 38.0 ± 1.60 %. Also, the developmental period from infestation to offspring production was, on an average, 47.3 ± 0.65 days, and the mean of offspring sex ratio was 84 ± 3.0 % females. On the other hand, the offspring production of *F. virgata* was

Table 1 Leaf tissue nutrients from cotton leaves harvested from median third of the cotton plant submitted to nitrogen fertilization and water stress conditions

Nutrients[a]	With nitrogen fertilization (+N)		Without nitrogen fertilization (−N)	
	Without water stress (+W)	With water stress (−W)	Without water stress (+W)	With water stress (−W)
Percentage in the leaf tissue sample				
N	2.53 ab	3.73 a	1.93 b	2.33 b
P	0.44 a	0.30 ab	0.32 ab	0.20 b
K	1.20 a	1.28 a	0.96 a	1.03 a
Na	0.06 ab	0.09 a	0.05 b	0.05 b
Ca	1.77 a	1.90 a	1.33 a	1.36 a
Mg	0.13 a	0.14 a	0.08 b	0.10 ab
ppm				
Zn	36 a	44 a	32 a	28 a
Cu	26 b	48 a	25 b	9 bc
Fe	130 a	140 a	52 b	44 b
Mn	22 a	26 a	17 a	19 a

Leaf samples were collected 55 days after emergence for nitrogen mineral analyses

[a] Mean values followed by same letter within rows do not differ by pair-wise Chi square test after the null hypothesis of equality was rejected at 0.05 significance levels

variable as a function of N fertilization and water-stress condition (Table 3). Despite the significance for both treatment effects (N fertilization and irrigation regimes), there was no interaction effect between these factors

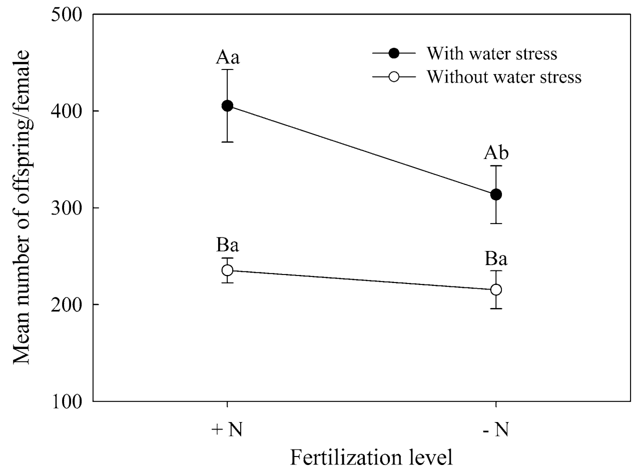

Fig. 1 The mean number of offspring produced per female of *F. virgata* reared on cotton plants submitted to fertilization levels (+N and −N) and irrigation regimes, characterizing plants under regular water supply and water stress. *Note*: Means (±SEM) under the *same capital letters* compare irrigation regimes within the same fertilization level (*vertical*); while means (±SEM) under the *same small letters* compare N fertilizations within the same irrigation regime (*horizontal*) (Fisher's test of ANOVA at 0.05 levels)

because the same pattern of greater offspring production was observed in water-stressed plants irrespective of N fertilization (both +N and −N) (Fig. 1).

The average offspring production was 359.5 ± 25.41 and 225.3 ± 11.62 nymphs/female on −W and +W plants, respectively, resulting in 37 % more offspring produced by females reared on −W cotton plants as compared to +W plants irrespective of N fertilization. Regarding the

Table 2 Fresh and dry weight, and number of bolls of cotton plants in response to N fertilization levels and irrigation regimes in the greenhouse (cotton plants were at 123 days after emergence) with N fertilization initiated for 20-day-old plants (six N fertilizations were made, spaced 10 days apart), without water (+W) and with (−W) water stress for 30-day-old plants

Fertilizations	Irrigation regimes	Fresh weight (g)	Dry weight (g)	Number of bolls
+N fertilization	−W	146.2 ± 10.23 b	71.0 ± 2.35 bc	3.1 ± 0.60 b
	+W	359.4 ± 32.46 a	124.8 ± 12.83 ab	10.1 ± 1.28 a
−N fertilization	−W	132.0 ± 13.80 b	63.8 ± 6.36 c	1.9 ± 0.43 b
	+W	334.8 ± 59.19 a	127.6 ± 25.03 a	8.8 ± 1.97 a

[a] Mean values (± SEM) followed by the same letter within column do not differ by Tukey HSD test at 0.05 significance level

Table 3 Results of two-way analysis of variance (ANOVA) for mealybug survival 25 days after infestation, development, and adult traits regarding N fertilization and irrigation regimes of cotton plants

Source of variation	*df*	Survival (%)		Developmental time + pre-oviposition period		Offspring production		Offspring sex ratio	
		F	*P*	*F*	*P*	*F*	*P*	*F*	*P*
N fertilization (N)	1	1.47	0.230	0.16	0.689	4.71	0.034	2.01	0.175
Irrigation regime (W)	1	0.21	0.646	2.00	0.163	25.52	<0.0001	0.18	0.678
N × W	1	0.50	0.481	0.21	0.650	1.22	0.273	2.32	0.146
Error	52								

condition of N fertilization, irrespective of the irrigation regime, mealybug females raised on cotton plants receiving supplementary N fertilization produced 320.3 ± 25.41 nymphs as compared to 264.5 ± 19.90 nymphs for females raised on plant without N supply. Thus, 18 % more offspring was produced by females fed cotton plants with increased N content.

Discussion

Leaf nutrient contents and plant developmental performance revealed significant effects of N fertilization and irrigation regimes studied. Cotton plants receiving successive N fertilizations and cultivated under water stress exhibited greater N content in leaves as compared to plants with fertilizations but not under water stress. These findings agree with other studies in that water stress (White 1969; Miles et al. 1982; Brodbeck and Strong 1987) and application of N fertilizers increase nitrogen content in plants and thereby increase the amount of N available to the herbivores (Mattson 1980; Bentz et al. 1995; Nevo and Coll 2001; Jiao et al. 2012). Furthermore, cotton plants without water stress showed better development than water-stressed plants, and plants receiving N fertilization developed more as compared to plants without N fertilizations. However, the water-stress condition was the major factor that contribute to the differences in the development of study plants (Table 2).

Nitrogen fertilization and water stress positively affected the offspring production of *F. virgata* with an additive effect. Plants subjected to water stress produced higher number of offspring and was even superior when N was applied. However, the studied condition of N fertilization and water stress did not interfere with the survival of the neonate nymphs and developmental times of *F. virgata*. Thus, in the light of our studied conditions, the results obtained indicate that successive N fertilization and water stress had only detectable effects on the reproductive output of *F. virgata*. This evidence suggests a straightforward conclusion that N-enriched cotton plants under water stress are more suitable for the mealybug offspring production; this is incompliance with previous data on better host plant quality to sap-sucking insects under both N fertilizations (Mattson 1980; White 1993; Jiao et al. 2012) and water stress (White 1969; Mattson and Haack 1987; Brodbeck and Strong 1987).

The results help us to explain the frequent outbreaks of mealybugs in cotton fields of the semiarid region of Brazil (Bastos et al. 2007; Torres et al. 2011; Silva-Torres et al. 2013), which is a common event at the end of cropping season when the rain becomes scarce. Also, these findings help us explicate the heavy infestations of mealybugs observed on cotton plants under water stress in the corners of cotton fields in the west of Bahia State, which is cultivated in the dry season and irrigated with pivot (J. B. Torres, personal observations).

Despite much information on the effects of water stress and N fertilization on sap-sucking insects, as discussed in the Introduction section, only few studies have evaluated the effect of these factors (N fertilizations: Lema and Mahungu 1983; Hogendorp et al. 2006; and plant water stress: Calatayud et al. 2002) on mealybug performance. The developmental time of the citrus mealybug *P. citri* was shorter when fed on coleus plants enriched with different concentrations of N (Hogendorp et al. 2006), while the mealybug *P. herreni* responded with faster development when fed on cassava plants under water stress (Calatayud et al. 2002). Furthermore, these two mealybug species (*P. citri* and *P. herreni*) exhibited high offspring production in the same conditions that partially corroborate with our data on *F. virgata.* It is interesting to note that the data are not standardized among the mealybugs, as the cassava mealybug *Phenacoccus manihoti* (Malite-Ferrero) (Hemiptera: Pseudococcidae) did not respond positively to cassava plants enriched with N fertilization (Lema and Mahungu 1983). Therefore, it seems that there are variations in response to N fertilizations and water stress among the mealybug species. The response can be of specific developmental or of reproductive trait, as for *F. virgata* in the present study.

In general, results of N fertilization show an improvement in herbivores performance (Mattson 1980; Rae and Jones 1992; White 1993; Hogendorp et al. 2006; Kerpel et al. 2006; Huberty and Denno 2006; Barros et al. 2007; Chen et al. 2008; Aqueel and Leather 2011). However, there are some divergences regarding the effect of plant water stress on herbivores. Huberty and Denno (2004) analyzed 82 studies and concluded that plants under water stress caused negative effect on sap-sucking insects, which contradicts the PSH supported by other authors (White 1969; Mattson and Haack 1987; Brodbeck and Strong 1987). According to Huberty and Denno (2004), under continuous water stress, the turgor pressure of the plant is negative and the insects are impeded to obtain nutrients from the plant sap. On the other hand, when the plants are subjected to discontinuous water stress, they become more suitable with enriched sap available to sap-sucking insects as the plant turgor pressure turn positive again under regular water supply. Thus, sap-sucking insects can exhibit better performance on plants subjected to intermittent water stress such as those short droughts during the summer rainy season. In our study, the cotton plants were continuously exposed to water stress during the study period duration of 30–123 days, and *F. virgata* performed reproductively better. The striped mealybug is a highly polyphagous and cosmopolitan species (Normark and

Johnson 2011) and thus potentially adapted to various species of host plants and climatic conditions.

The survival success and the sex ratio of *F. virgata* offspring produced of *F. virgata* were not affected by the condition of cotton plants studied. About 38 % of the released neonate nymphs reached adult stage across all treatments. The loss of nymphs is especially during the crawler stage, when dispersing over the plant, and could account for the remaining nymphs not reaching adult stage. According to Strickland (1950), Grasswitz and James (2008), and Silva-Torres et al. (2013), several factors can determine the success of *F. virgata* survival on cotton plants including wind and rain and plant morphology. Regarding the sex ratio, in most mealybugs, it is determined by the parental female (Ross et al. 2010). According to Ross et al. (2011), the sex ratio of *P. citri* is variable as a function of food shortage. This result indicates that variations in the amount of food intake by the female influences the offspring sex ratio. Thus, we hypothesized that the variable conditions of the cotton plant (N fertilizations and irrigation regimes) may have altered the proportion of females and males in the offspring produced by females of *F. virgata* raised on improved host characteristics through fertilization and water stress. However, our results do not support this hypothesis and require more investigation to ascertain regarding the sex ratio of the offspring produced by *F. virgata*, because, beyond host quality and host species, other factors such as variation in temperature, population densities, and the age of the female at first mating are important, as observed for other mealybug species (Nelson-Rees 1960; Varndell and Godfray 1996; Ross et al. 2010, 2011). The knowledge of offspring sex ratio adjustment may help adopt integrated pest management strategies such as survey and mass capture of males using male-attracting semiochemicals; meanwhile, this practice become useless for conditions favoring only female offspring production.

The present study aimed to obtain information about the performance of striped mealybug *F. virgata* infesting cotton plants with respect to N fertilization and water stress, considering that the latter is often observed in arid areas and may also occur during rainy summer season due to short periods of drought. Among our findings, we can highlight that the offspring production of *F. virgata* was nearly twofold higher on water-stressed plants with successive N fertilizations. The offspring production was increased by 37 % as a function of water stress and 18 % as a function of N fertilization, while developmental times and survival were similar across the studied conditions. Therefore, cotton plants either enriched with N fertilizations or water-stressed are suitable host for *F. virgata* infestation, especially when these conditions occur simultaneously. To counteract these favorable conditions to the pest, attention should be paid in risk areas caused by prolonged drought periods. Therefore, to avoid generalized *F. virgata* infestation, fertilization of cotton plants should be judiciously managed, including managing of irrigation as well, whenever possible, to avoid successful offspring production and survival of the pest.

Acknowledgments This research was partially supported by the agencies “Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco (FACEPE)” and the “Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)” through the projects APQ-0538-5.01/10 and PNPD No. 02544/09-1, respectively. Also, we would like to thank Alessandra Rung (Plant Pest Diagnostics Branch, California Department of Food and Agriculture, Sacramento, CA) and Douglas Miller (Systematic Entomology Laboratory, ARR-USDA, Beltsville, MD) for identifying the striped mealybug species.

References

Aqueel MA, Leather SR (2011) Effect of nitrogen fertilizer on the growth and survival of *Rhopalosiphum padi* (L.) and *Sitobion avenae* (F.) (Homoptera: Aphididae) on different wheat cultivars. Crop Prot 30:216–221

Archer TL, Bynum ED Jr, Onken AB, Wendt CW (1995) Influence of water and nitrogen fertilizer on biology of the Russian wheat aphid (Homoptera: Aphidae) on wheat. Crop Prot 14:165–169

Barros R, Degrande PE, Fernandes MG, Nogueira RF (2007) Efeitos da adubação nitrogenada em algodoeiro sobre a biologia de *Aphis gossypii* Glover (Hemiptera: Aphididae). Neotrop Entomol 36:752–758

Bastos CS, Almeida RP, Vidal Neto FC, Araújo GP (2007) Ocorrência de *Planococcus minor* Maskell (Hemiptera: Pseudococcidae) em algodoeiro no Nordeste do Brasil. Neotrop Entomol 36:625–628

Bentz JA, Reeves JIII, Barbosa P, Francis B (1995) Within-plant variation in nitrogen and sugar content of poinsettia and its effects on the oviposition pattern, survival, and development of *Bemisia argentifolii*. Environ Entomol 24:271–277

Brodbeck B, Strong D (1987) Amino acid nutrition of herbivorous insects and stress to host plants. In: Barbosa P, Schultz J (eds) Insect outbreaks: ecological and evolutionary perspectives. Academic Press, San Diego, pp 347–364

Calatayud PA, Polanía MA, Seligmann CD, Bellotti AC (2002) Influence of water-stressed cassava on *Phenacoccus herreni* and three associated parasitoids. Entomol Exp Appl 102:163–175

Chen Y, Ruberson JR, Olson DM (2008) Nitrogen fertilization rate affects feeding, larval performance, and oviposition preference of the beet armyworm, *Spodoptera exigua*, on cotton. Entomol Exp Appl 126:244–255

Fennah RT (1959) Nutritional factors associated with the development of mealybugs in cacao. Rep Cacao Res InstTrinidad 1957–1958:18–28

Ferreira ECB, Silva CAD, Viana DL, Sousa SL (2009) A diversidade genética existente entre cultivares de algodão influencia de forma diferente populações de *Phenacoccus solenopsis* (Hemiptera: Pseudococcidae)? In: IV Encontro de Produção Científica da Embrapa Algodão – EPC. Campina Grande, Centro Nacional de Pesquisa de Algodão, pp 14

Gershenzon J (1984) Changes in the levels of plant secondary metabolites under water and nutrient stress. Recent Adv Phytochem 18:273–320

Grasswitz TR, James DG (2008) Movement of grape mealybug, *Pseudococcus maritimus*, on and between host plants. Entomol Exp Appl 129:268–275

Hogendorp B, Cloyd RA, Swiader JM (2006) Effect of nitrogen fertility on reproduction and development of citrus mealybug, *Planococcus citri* Risso (Homoptera: Pseudococcidae), feeding on two colors of coleus, *Solenostemon scutellarioides* L. Codd. Environ Entomol 35:201–211

Hsiao TC (1973) Plant responses to water stress. Annu Rev Plant Physiol 24:519–570

Huberty AF, Denno RF (2004) Plant water stress and its consequences for herbivorous insects: a new synthesis. Ecology 85:1383–1398

Huberty AF, Denno RF (2006) Consequences of nitrogen and phosphorous limitation for the plant performance of two plant hoppers with divergent life-history strategies. Oecologia 149:444–4556

Inbar MI, Doostdar H, Mayer RT (2001) Suitability of stressed and vigorous plants to various insect herbivores. Oikos 94:228–235

Jadoskil SO, Saito LR, Prado C, Lopes EC, Sales LLSR (2010) Characteristics of the Nitrate leaching in intensive farming areas. Pesqui Apl Agrotec 3:201–210

Jansson RK, Leibee GL, Sanchez CA, Lecrone SH (1991) Effects of nitrogen and foliar biomass on population parameters of cabbage insects. Entomol Exp Appl 61:7–16

Jiao X, Wang WXS, Wu Q, Zhou L, Pan H, Liu B, Zhang Y (2012) Host preference and nymph performance of B and Q putative species of *Bemisia tabaci* on three host plants. J Pest Sci 85:423–430

Kerpel SM, Soprano E, Moreira GRP (2006) Effect of nitrogen on *Passiflora suberosa* L. (Passifloraceae) and consequences for larval performance and oviposition in *Helconius eratophyllis* (Fabricius) (Lepidoptera: Nymphalidae). Neotrop Entomol 35:192–200

Larsson D (1989) Stressful times for the plant stress-insect performance hypothesis. Oikos 56:277–283

Lema KM, Mahungu NM (1983) Effects of fertilizer applications on postembryonic development and reproduction of the cassava mealybug. In: Proceedings of the second triennial symposium of the international society for the tropical root crops. Africa Branch, Douala, Cameroon, pp 231

Mattson WD (1980) Hebivory in relation to plant nitrogen content. Annu Rev Ecol Syst 11:119–161

Mattson WJ, Haack RA (1987) The role of drought in outbreaks of plant-eating insects. Bioscience 37:110–118

Miles PW, Aspinall D, Rosenberg L (1982) Performance of the cabbage aphid, *Brevicoryne brassicae* (L.), on water-stressed rape plants, in relation to the changes in their chemical composition. Aust J Zool 30:337–345

Miranda JE, Nascimento VL, Tripode BM, Abreu TPF, Anjos DE (2011) Suscetibilidade de *Phenacoccus solenopsis* a inseticidas. In: 8° Congresso Brasileiro de Algodão, 1° Cotton Expo, São Paulo. Evolução da cadeia para construção de um setor forte: Anais. Campina Grande, Embrapa Algodão, pp 274–280

Nelson-Rees WA (1960) A study of sex predetermination in the mealybug *Planococcus citri* (Risso). J Exp Zool 144:111–137

Nevo E, Coll M (2001) Effect of nitrogen fertilization on *Aphis gossypii* (Homoptera: Aphididae): variation in size, color, and reproduction. J Econ Entomol 94:27–32

Normark BB, Johnson NA (2011) Niche explosion. Genetica 139:551–564

Oliveira MD, Barbosa PRR, Silva-Torres CSA, Torres JB (2013) Performance of the striped mealybug *Ferrisia virgata* Cockerell (Hemiptera: Pseudococcidae) under variable conditions of temperature and mating. Neotrop Entomol 43:1–8

Oliveira MD, Silva-Torres CSA, Torres JB, Oliveira JEM (2014) Population growth and within-plant distribution of the striped mealybug *Ferrisia virgata* (Cockerell) (Hemiptera, Pseudococcidae) on cotton. Rev Bras Entomol 58:71–76

Orlando Filho J, Zambello Jr E (1983) Diagnose foliar. In: Orlando Filho J (ed) Nutrição e adubação da cana-de-açúcar no Brasil. Piracicaba, IAA/Planalsucar, pp 125–152

Panizzi AR, Parra JRP (1991) Ecologia nutricional de insetos e suas implicações no manejo de pragas. São Paulo, Manole

Price PW (1991) Plant vigor and herbivore attack. Oikos 62:244–251

Price PW, Clancy KM (1986) Multiple effects of precipitation on *Salix lasiolepis* and populations of the stem-galling sawfly, *Euura lasiolepis*. Ecol Res 1:1–14

Rae DJ, Jones RE (1992) Infuence of host nitrogen levels on development, survival, size and population dynamics of sugarcane mealybug, *Saccharicoccus saccari* (Cockerell) (Homoptera: Pseudococcidae). Aust J Zool 40:327–342

Ross L, Langenhof MBW, Pen I, Beukeboom LW, West SA, Shuker DM (2010) Sex allocation in a species with Paternal Genome Elimination: clarifying the role of crowding and female age in the mealybug *Planococcus citri*. Evol Ecol Res 12:89–104

Ross L, Dealey EJ, Beukeboom LW, Shuker DM (2011) Temperature, age of mating and starvation determine the role of maternal effects on sex allocation in the mealybug *Planococcus citri*. Behav Ecol Sociobiol 65:909–919

SAS Institute (2001) SAS/STAT User's guide, version 8.02, TS level 2MO. SAS Institute Inc., Cary

Silva-Torres CSA, Oliveira MD, Torres JB (2013) Host selection and establishment of striped mealybug, F*errisia virgata*, on cotton cultivars. Phytoparasitica 41:31–40

Staley JT, Mortimer SR, Masters GJ, Morecroft MD, Brown VK, Taylor ME (2006) Drought stress differentially affects leaf-mining species. Ecol Entomol 31:460–469

Strickland AH (1950) The dispersal of Pseudococcidae (Hemiptera–Homoptera) by air currents in the Gold Coast. Proc R Entomol Soc Lond 25:1–9

Torres JB, Oliveira MD, Lima MS (2011) Cochonilhas farinhentas: potenciais problemas para o algodão brasileiro. Recife, Brasil, Universidade Federal de Pernambuco (Informativo REDALGO 005)

Varndell NP, Godfray HCJ (1996) Facultative adjustment of the sex ratio in an insect (*Planococcus citri*, Pseudococcidae) with paternal genome loss. Evolution 50:2100–2105

White TCR (1969) An index to measure weather-induced stress of trees associated with outbreaks of psyllids in Australia. Ecology 50:905–909

White TCR (1993) The inadequate environment: nitrogen and the abundance of animals. Springer, New York