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WITHIN PLANT DISTRIBUTION AND DYNAMICS OF *HYADAPHIS FOENICULI* (HEMIPTERA: APHIDIDAE) IN FIELD FENNEL INTERCROPPED WITH NATURALLY COLORED COTTON

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Abstract

Intercropping fennel (*Foeniculum vulgare* Mill.) with naturally colored cotton (*Gossypium hirsutum* L.) may provide a beneficial socioeconomic, ecological and environmental alternative for recuperating agribusiness in fennel and cotton cultivations in northeast Brazil because these crops do not compete for nutrients. The objectives of this study were to investigate the vertical and horizontal distribution of *Hyadaphis foeniculi* (Pass.) within fennel plants and its population dynamics in fennel crops and fennel intercropped with naturally colored cotton as a function of plant age during 2 fennel seasons by examining plants throughout the entire growing seasons. The vertical and horizontal distributions and the dynamics of the fennel aphids on the monocultured fennel and fennel intercropped with cotton were determined at intervals of 7 days, sampling 5 whole plants per plot from 55 days after transplanting the fennel seedlings until the first harvest (195 days after transplanting). The vertical distribution of apterous or alate aphids on the fennel plants evidenced no significant interactions within the cropping system, plant age, or vertical region of the plant, or between the cropping system and the vertical region of the plant. However for the number of fennel aphids per plant, there was an interaction between cropping system and plant age (apterous aphids) and between plant age and vertical region of the plant (apterous or alate aphids). In the fennel system, the apterous aphid population peaked at 153 and 188 days after transplanting, whereas the alate aphid population peaked at 139 and 174 days after transplanting. In the intercropped fennel/cotton system, the apterous aphid population peaked at 188 days after transplanting, and the alate aphid population peaked at 195 days after transplanting. The numbers of apterous aphids found per fennel plant in the monocultured fennel for the entire study were significantly higher than the numbers found in the fennel-cotton intercropped system.

The results of our study are extremely important for understanding the vertical and horizontal distribution of *H. foeniculi* on fennel plants in both monoculture and the fennel-cotton intercropping system and may be useful in decision-making in relation to implementing controls and determining the timing of population peaks of this important fennel pest.

Key Words: Fennel, *Hyadaphis foeniculi,* cotton with colored fibers, intercropping system, dynamics, behavior

Resumo

O consórcio de erva-doce (*Foeniculum vulgare* Mill.) com algodão com fibras naturalmente coloridas, poderá ser uma alternativa sócio-econômica, ecológica e ambiental para recuperar o agronegócio dos cultivos da erva-doce e do algodão no nordeste do Brasil, já que essas culturas não competem entre si por nutrientes. Os objetivos da pesquisa foram estudar as distribuições vertical e horizontal de *Hyadaphis foeniculi* (Pass.) nas plantas de erva-doce e suas dinâmicas populacionais na cultura da erva-doce solteira e consorciada com algodão com fibras coloridas em função da idade, durante dois anos, examinando as plantas durante o ciclo da cultura. As distribuições vertical e horizontal e as dinâmicas de pulgões da erva-doce nas culturas de erva-doce e erva-doce consorciada com algodão foram determinadas em intervalos de sete dias, amostrando totalmente cinco plantas por parcela, a partir de 55 dias após o transplantio das plantinhas de erva-doce até a primeira colheita (195 dias após o transplantio). A distribuição vertical de pulgões ápteros ou alados dentro das plantas de erva-doce não evidenciaram interações significativas entre sistema de cultivo, idade da

planta e região da planta ou entre sistema de cultivo e região da planta. No entanto, ocorreu interação entre sistema de cultivo e idade da planta (pulgões ápteros) e entre idade da planta e região da planta (pulgões ápteros ou alados) para o número de pulgões por planta de erva-doce. No sistema de erva-doce, a população de pulgões ápteros atingiu dois picos, um aos 153 dias e outro aos 188 dias, após o transplante; enquanto que a população de pulgões alados atingiu dois picos, um aos 139 dias e outro aos 174 dias, após o transplante. No sistema de consórcio de erva-doce com algodão, a população de pulgões áptero atingiu um pico aos 188 dias, após o transplante, enquanto, a população de pulgões alado atingiu um pico aos 195 dias, após o transplante. Os resultados do nosso estudo são extremamente importantes para a compreensão da distribuição vertical e horizontal de *H. foeniculi* em plantas de erva-doce em ambos sistemas de monocultura e consórcio de erva-doce com algodão com fibras naturalmente coloridas e ser útil na tomada de decisão, implementação de controles e determinar o momento de picos populacionais dessa importante praga da erva-doce.

Palavras Chave: Erva-doce, *Hyadaphis foeniculi,* algodão com fibras coloridas, sistema de consórcio, dinâmica, comportamento

Fennel (*Foeniculum vulgare* Mill.; Apiales: Apiaceae)) is native to Mediterranean coastal regions (Tanira et al. 1996; Marino et al. 2007; Aprotosoaie et al. 2010; Bayazit 2010; Hendawy & El-Din 2010; He & Huang 2011) and occurs naturally throughout Europe and North America. It was introduced to Brazil by the first settlers and grew readily in the states of Bahia, Sergipe, Paraíba and Pernambuco (Ferreira & Silva 2004). Fennel is known for its therapeutic properties (digestive, diuretic and anti-inflammatory) (El-Awadi & Hassan 2011) and culinary uses (soups, pastries and cakes), and it has insecticidal (Abramson et al. 2006;Abramson et al. 2007a; Abramson et al. 2007b; Hendawy & El-Din 2010) and fungicidal properties (Singh et al. 2006). It therefore has a guaranteed market in the northeast of Brazil and is important to family farming in the region (Ramalho et al. 2012a).

The various factors that impair fennel yield and seed quality in Brazil include insect pests, particularly the fennel aphid *Hyadaphis foeniculi* (Pass.) (Hemiptera: Aphididae). *H. foeniculi* is a cosmopolitan species and vector for at least 12 types of virus, including mosaic potyvirus, yellow spot luteovirus and latent carlavirus (Ferreira & Silva 2004). By continually sucking the sap, it causes flowers and fruits to wilt and dry up (Abramson et al. 2007b). It also produces a secretion, known as 'honeydew,' that is favorable to the development of the fungus *Capnodium* spp. and leads to the formation of sooty mold (Lazzari & Lazzarotto 2005); this mold impedes plant respiration and reduces photosynthesis surface area, weakening the plant (Leite et al. 2006).

In the state of Paraíba, *H. foeniculi* generally reproduces during hot periods, forming colonies inside the blooms (Abramson et al. 2007b). The fluctuation of the aphid population is highly seasonal, and populations can vary from one year to another. This variation is related to the species' feeding habits and the availability and phenology of the host plant (Lazzari & Lazzarroto 2005).

The influence of the host plant on the success of a plant-feeding insect species can be measured in terms of 3 factors: the stimuli that lead the insect to locate and choose the plant, the plant conditions that lead the insect to begin and continue feeding, and finally, the plant's characteristics (particularly from a nutritional viewpoint) that guarantee the development of the insect and its progeny (Fernandes et al. 2001). Furthermore, population fluctuation patterns for a given insect species can differ from one geographic region to another, from one colony to another in the same region over time and from one simultaneously developing nearby population to another (Cividanes & Santos 2003).

Studies have been conducted on the distribution of aphids on wheat plants (*Triticum aestivum* L.) (Boeve & Weiss 1998; Gianoli 1999), spring greens (*Brassica oleracea* L. var. acephala DC.) (Cividanes & Santos 2003), banana (*Musa* spp.) (Robson et al. 2006), plants in the Chenopodiaceae family (Tóth et al. 2006), soybean (*Glycine max* (L.) Merr.) (McCornack et al. 2008) and black pepper (*Capsicum annuum* L.) (Rahman et al. 2010). Additional studies have been performed in both monoculture and intercropped systems of upland cotton (*Gossypium hirsutum* L.) × maize (*Zea mays* L.) × sorghum [*Sorghum bicolor* (L.) Moen.] × common bean (*Phaseolus vulgaris* L.) or sesame (*Sesamum indicum* L. (Gonzaga et al. 1991), tomato (*Lycopersicum esculentum* Mill.) × aromatic and/or medicinal crops (Carvalho et al. 2009), and fennel (*F. vulgare*) × dill (*Anethum graveolens* L.) (Carrubba et al. 2008). However, we are still in the early stages of obtaining information on the distribution of *H. foeniculi* within the fennel plant when intercropped with naturally colored cotton. The spatial distribution of insects is one of the ecological properties that characterize various species (Taylor 1984). Therefore, understanding the population dynamics and vertical distribution of insect pests and their enemies on host plants is fundamental for developing integrated pest control programs (Cividanes & Santos 2003; Fernandes et

al. 2012a; Fernandes et al. 2012b). *Foeniculum vulgare* is grown both as a monoculture and intercropped with other plant species of commercial interest in the northeast of Brazil (Ferreira & Silva 2004; Carvalho et al. 2009; Malaquias et al. 2010; Ramalho et al. 2012a). Intercropping can influence insect population dynamics, increasing or decreasing the population density of pests and natural enemies in the agroecosystem (Gonzaga et al. 1991; Cividanes & Yamamoto 2002). It is thought that intercropping fennel with naturally-colored cotton (*Gossypium hirsutum* L.) could provide a socioeconomic, ecological and environmental alternative, since these crops do not compete for nutrients.

Studies have emphasized the importance of arthropod distribution on crop plots Kuehland & Fye 1972; Rodrigues et al. 2010) and plants (Fernandes et al. 2012a; Fernandes et al. 2012b). However, there is no information on the vertical and horizontal distribution of *H. foeniculi* as a function of the age of fennel intercropped with cotton. Given the need for effective control of this pest on fennel intercropped with cotton, it is important to determine whether the behavior of *H. foeniculi* in relation to its distribution within the plant is affected over time. This information may help optimize decision making in integrated fennel aphid management programs. Therefore, the aims of this study were to investigate the vertical and horizontal distribution of *H. foeniculi* on fennel plants and its population dynamics in fennel crops and fennel intercropped with naturally colored cotton as a function of plant age during 2 fennel seasons by examining plants throughout the entire growing seasons. Fennel intercropped with cotton with colored fibers is an alternative for recuperating agribusiness in fennel and cotton cultivations in northeast Brazil. *Hyadaphis foeniculi* reduced the fennel seed yield by 80% in the fennel plots compared with an approximate 30% reduction for all intercropping systems tested (Ramalho et al. 2012a).

Materials and Methods

Study Area and Fennel and Cotton Cultivars

The study was conducted in the Experimental Station of Embrapa Algodão in the counties of Montadas and Lagoa Seca, Paraíba, Brazil, a rural wetland microregion at an elevation of 634 m, S 7°10' 5" W 35°51'13", during the 2008 and 2009 agricultural years. Fennel (*F. vulgare*, cultivar 'Montadas') was examined as a monoculture and intercropped with naturally colored cotton (*G. hirsutum*, cultivar 'BRS Safira') under dry land conditions. The field plots were established in the second wk of Apr in 2008 and between the first and second week of May in 2009. No insecticides were used to control pests during the study.

Experimental Design

A randomized block design was used, with 2 treatments (fennel and fennel intercropped with cotton) and 4 replications.

The experimental unit in the intercropped fennel plots consisted of 3 rows of cotton between double rows of fennel (transplanted upon reaching 20 cm in height), totaling 8 rows of fennel and 9 rows of cotton, all with a row length of 21 m (Ramalho et al. 2012a) (Fig. 1). In the intercropped plots, the spacing between fennel rows was 1.50 m, the distance between the fennel row and the cotton row was 1.50 m, the cotton rows were spaced at 1.00 m and the cotton plants were spaced within row at 0.20 m (Ramalho et al. 2012a). In the fennel plot, the rows were spaced at 1.50 m, and the plants were spaced within row at 0.50 m, totaling 15 rows of fennel, all with a row length of 21 m.

Arthropod Species Sampling

The vertical and horizontal distributions and the dynamics of the fennel aphids on the monocultured fennel and fennel intercropped with cotton were determined at intervals of 7 days, sampling 5 whole plants per plot starting 55 days after

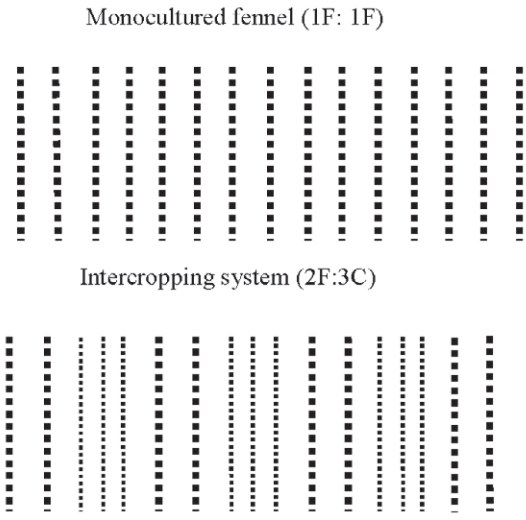

Fig. 1. Layout of experimental units in the fennel-cotton intercropping system (lower panel) and the monoculture system (upper panel). Lower Panel: The intercropping system was arranged in strips, i.e., 2 rows of fennel alternating with 3 rows of cotton. The rows of fennel were spaced 1.5 m apart, the space, and the space between the fennel row and the adjacent cotton row was 1.5.m, and the cotton rows were spaced 1.0 m apart. Lower Panel: The monoculture of fennel was not arranged in strips, but the fennel rows were uniformly spaced 1.5 m apart.

transplanting the fennel seedlings and continuing until the first harvest (195 days after transplanting).

The numbers of apterous and alate aphids were ascertained, and their specific locations were recorded using the node on the plant's main stem as a reference (lowest node = 23, highest node = 1). The aphids on the apical and lateral leaves and umbels were also counted. The apical and lateral umbels sprout from the apical and lateral meristems, respectively. The apical meristems are located at the ends of the stems and branches of the fennel plants, whereas the lateral meristems are located along the plant stems and branches.

Data Analysis

Tests were conducted for the normality (Kolmogorov D: normal test) and homogeneity (Bartlett's test) of the number of apterous or alate aphids recorded per plant; when necessary, the data were converted to square roots of (x + 0.5). The mean numbers of aphids quantified were subjected to 3-way analysis of variance (ANOVA): cropping system, plant age and plant region, and the means were compared using the Student-Newman-Keuls test (P = 0.05). Aphid percentages were linked to the positions of the nodes vertically and upward (lowest node = 23 and highest node = 1) or the positions of the leaves and fruit structures on the branches using PROC REG (SAS Institute 2006).

Results

Considering the year-to-year data, analyses of the season-long averages for the numbers of apterous or alate aphids showed that the number of apterous or alate aphids per fennel plant in fennel ($F_{(1, 9)} = 1.01$; $P > 0.2111$) and fennel intercropped with cotton ($F_{(1, 9)n} = 0.141$; $P > 0.1349$) did not differ between years. Therefore, the analyses were conducted using the pooled data.

The numbers of apterous aphids ($F_{CS\ (1,\ 3)} = 53.84$; $P < 0.0052$) and alate aphids ($F_{CS\ (1,\ 3)} = 18.44$; $P < 0.0232$) found per fennel plant in the monocultured fennel (27,922 apterous and 703 alate aphids) for the entire study were significantly higher than the numbers found in the fennel-cotton intercropped system (13,012 apterous and 369 alate aphids).

The vertical distribution of aphids on the fennel plants evidenced no significant interactions among the cropping system, plant age and plant region (apterous aphids: $F_{CS\ by\ A\ by\ R\ (40,\ 375)} = 0.62$, $P = 0.9687$; alate aphids: $F_{CS\ by\ A\ by\ R\ (40,\ 375)} = 0.69$, $P = 0.9250$) or between the cropping system and plant region (apterous aphids: $F_{CS\ by\ R\ (2,\ 375)} = 1.05$, $P = 0.3523$; alate aphids: $F_{CS\ by\ R\ (2,\ 375)} = 0.44$, $P = 0.6451$) (Table 1). However, there was an interaction between cropping system and plant age (apterous aphids: $F_{SC\ by\ A\ (20,\ 375)} = 1.74$; $P < 0.0260$; alate aphids: $F_{SC\ by\ A\ (20,\ 375)} = 1.91$; $P < 0.0107$) and between plant age and region (apterous aphids: $F_{A\ by\ R\ (40,\ 375)} = 2.00$; $P < 0.0005$; alate aphids: $F_{A\ by\ R\ (40,\ 375)} = 1.42$; $P < 0.0513$) (Table 1) for the num-

Table 1. Summaries of model parameters revealed by 3-way analysis of variance (ANOVA) of the effects of cropping systems[1], plant age[2] and vertical plant region[3] on the number of fennel aphids *Hyadaphis foeniculi* found per fennel plant.

Source	Model	DF	*F* ratio	Prob > *F*
Apterous aphid (n)	Model	128	4.34	0.0001
	Cropping system (CS)	1	9.13	0.0027
	Age (A)	20	17.46	0.0001
	Plant region (R)	2	20.14	0.0001
	CS x A	20	1.74	0.0260
	CS x R	2	1.05	0.3523
	A x R	40	2.00	0.0005
	CS x A x R	40	0.62	0.9687
Alate aphids (n)	Model	128	2.32	0.0001
	Cropping system (CS)	1	3.58	0.0544
	Age (A)	20	7.05	0.0001
	Plant region (R)	2	9.91	0.0001
	CS x A	20	1.91	0.0107
	CS x R	2	0.44	0.6451
	A x R	40	1.42	0.0513
	CS x A x R	40	0.69	0.9250

[1]Cropping systems: Monocultured fennel and fennel intercropped with cotton.
[2]Crop ages: 55, 62, 69, 76, 83, 90, 97, 104, 11, 118, 125, 132 139, 146, 153, 160, 167, 174, 181, 188 and 195 days. [3]Plant regions: Basal, median and apical.

ber of fennel aphids per plant. These results indicate that, irrespective of the cropping system, the number of apterous or alate aphids found in each region of the fennel plant varied according to the age of the plant.

From transplanting the fennel seedlings up to 118 days (intercropped fennel) or 132 days (fennel), no apterous or alate aphids were found in the cropping systems examined (Tables 2 and 3).

From 139 days to 195 days after transplanting, the fennel plants became infested with apterous and alate aphids. More aphids were found on plants in the fennel system than on plants in the fennel-cotton intercropped system (Tables 2 and 3), except at 195 days after transplanting. At this time point, the numbers of alate aphids per fennel plant were higher in the fennel-intercropped system than in the fennel system.

The numbers of apterous and alate aphids per fennel plant in the fennel system were higher at 188 days (Table 2) and 181 days (Table 3) after transplanting the fennel plants. However, in the intercropped fennel-cotton system, the numbers of apterous and alate aphids were higher at 188 days (Table 2) and 195 days (Table 3) after transplanting the fennel plants. At 139, 146, 181, 188 and 195 days after transplanting the fennel plants, we found more apterous aphids in the apical region than in the other regions of the fennel plants (Table 4); from 160 to 167 days after transplanting, we found more apterous aphids in the median region than in the other regions of the fennel plants. However, at 153 and 174 days after transplanting, the number of apterous aphids found in the apical region of the fennel plants was similar to the number found in the median region (Table 4).

The highest numbers of apterous aphids quantified in the apical, median and basal regions of the fennel plants were found 188 days after transplanting (Table 4). We observed that at 139, 174, 188 and 195 days after transplanting, more alate aphids were found in the apical region than in the other plant regions (Table 5).

At 146, 153 and 160 days after transplanting, the number of alate aphids recorded in the api-

Table 2. Number of apterous aphids per plant (mean ± SD) found on leaves and umbels of fennel plants as a function of cropping system and plant age ($F_{\text{CS BY A (20, 375)}} = 1.74$, $P < 0.0260$).

Plant age (day)[1]	Cropping system[2]: Monocultured fennel	Fennel intercropped with cotton
55	0.00 ± 0.00 aE	0.00 ± 0.00 aE
62	0.00 ± 0.00 aE	0.00 ± 0.00 aE
69	0.00 ± 0.00 aE	0.00 ± 0.00 aE
76	0.00 ± 0.00 aE	0.00 ± 0.00 aE
83	0.00 ± 0.00 aE	0.00 ± 0.00 aE
90	0.00 ± 0.00 aE	0.00 ± 0.00 aE
97	0.00 ± 0.00 aE	0.00 ± 0.00 aE
104	0.00 ± 0.00 aE	0.00 ± 0.00 aE
111	0.00 ± 0.00 aE	0.00 ± 0.00 aE
118	0.00 ± 0.00 aE	0.56 ± 0.08 aE
125	0.00 ± 0.00 aE	0.00 ± 0.00 aE
132	0.00 ± 0.00 aE	0.00 ± 0.00 aE
139	2.35 ± 0.87 aD	0.28 ± 0.05 bE
146	1.37 ± 0.45 aD	0.00 ± 0.00 bE
153	3.54 ± 0.87 aD	0.00 ± 0.00 bE
160	27.13 ± 5.78 aB	0.01 ± 0.00 bE
167	19.54 ± 4.65 aB	3.51 ± 0.77 bD
174	23.98 ± 5.46 aB	8.37 ± 2.85 bC
181	20.43 ± 5.00 aB	12.03 ± 2.76 bB
188	36.06 ± 7.76 aA	28.45 ± 6.12b A
195	11.03 ± 3.76 aC	14.58 ± 3.09 aB

[1]After the fennel plant was pruned.

[2]Means with the same lower case letter within rows and means with a common upper case letter within columns did not differ significantly in the Student-Newman-Keuls test ($P = 0.05$).

Table 3. Number of alate aphids per plant (mean ± SD) found on leaves and umbels of fennel plants as a function of cropping system and plant age ($F_{\text{CS BY A (20, 375)}} = 1.91$, $P < 0.0107$).

Plant age (day)[1]	Cropping system[2]: Monocultured fennel	Fennel intercropped with cotton
55	0.00 ± 0.00 aE	0.00 ± 0.00 aD
62	0.00 ± 0.00 aE	0.00 ± 0.00 aD
69	0.00 ± 0.00 aE	0.01 ± 0.00 aD
76	0.00 ± 0.00 aE	0.00 ± 0.00 aD
83	0.00 ± 0.00 aE	0.00 ± 0.00 aD
90	0.00 ± 0.00 aE	0.00 ± 0.00 aD
97	0.00 ± 0.00 aE	0.00 ± 0.00 aD
104	0.00 ± 0.00 aE	0.00 ± 0.00 aD
111	0.00 ± 0.00 aE	0.00 ± 0.00 aD
118	0.00 ± 0.00 aE	0.05 ± 0.00 aD
125	0.00 ± 0.00 aE	0.00 ± 0.00 aD
132	0.00 ± 0.00 aE	0.00 ± 0.00 aD
139	0.15 ± 0.04 aDE	0.02 ± 0.00 bD
146	0.02 ± 0.00 aE	0.00 ± 0.00 aD
153	0.02 ± 0.00 aE	0.00 ± 0.00 aD
160	0.28 ± 0.08 aD	0.00 ± 0.00 bD
167	0.49 ± 0.09 aC	0.13 ± 0.0.02 bCD
174	0.61 ± 0.09 aBC	0.27 ± 0.04 bC
181	1.14 ± 0.12 aA	0.13 ± 0..01 bCD
188	0.66 ± 0.08 aBC	0.45 ± 0.08 bB
195	0.31 ± 0.07 bC	0.88 ± 0.09 aA

[1]After the fennel plant was pruned.

[2]Means with the same lower case letter within rows and means with a common upper case letter within columns did not differ significantly in the Student-Newman-Keuls test ($P = 0.05$).

TABLE 4. NUMBER OF APTEROUS APHIDS (MEAN ± SD) FOUND ON LEAVES AND UMBELS OF FENNEL PLANTS AS A FUNCTION OF AGE AND VERTCAL PLANT REGION ($F_{R \text{ BY } A (40, 375)} = 2.00$, $P < 0.0005$).

Plant age (day)[1]	Plant region[2]		
	Apical	Median	Basal
55	0.00 ± 0.00 aF	0.00 ± 0.00 aD	0.00 ± 0.00 aD
62	0.00 ± 0.00 aF	0.00 ± 0.00 aD	0.00 ± 0.00 aD
69	0.00 ± 0.00 aF	0.00 ± 0.00 aD	0.00 ± 0.00 aD
76	0.00 ± 0.00 aF	0.00 ± 0.00 aD	0.00 ± 0.50 aD
83	0.00 ± 0.00 aF	0.00 ± 0.00 aD	0.00 ± 0.00 aD
90	0.00 ± 0.00 aF	0.00 ± 0.00 aD	0.00 ± 0.00 aD
97	0.00 ± 0.00 aF	0.00 ± 0.00 aD	0.00 ± 0.00 aD
104	0.00 ± 0.00 aF	0.00 ± 0.00 aD	0.00 ± 0.00 aD
111	0.00 ± 0.00 aF	0.00 ± 0.00 aD	0.00 ± 0.00 aD
118	0.84 ± 0.03 aF	0.00 ± 0.00 aD	0.00 ± 0.00 aD
125	0.00 ± 0.00 aF	0.00 ± 0.00 aD	0.00 ± 0.00 aD
132	0.00 ± 0.00 aF	0.00 ± 0.00 aD	0.00 ± 0.00 aD
139	3.13 ± 0.99 aE	0.81 ± 0.02 bD	0.00 ± 0.00 cD
146	2.04 ± 0.75 aE	0.02 ± 0.00 bD	0.00 ± 0.00 bD
153	2.81 ± 0.87 aE	1.64 ± 0.32 aD	0.87 ± 0.05 aD
160	13.90 ± 4.89 bD	26.81 ± 7.08 aB	0.00 ± 0.00 cD
167	13.40 ± 3.89 bD	20.78 ± 5.67 aB	0.40 ± 0.02 cD
174	23.17 ± 6.98 aC	23.59 ± 5.89 aB	1.77 ± 0.45 bC
181	31.85 ± 7.77 aB	16.56 ± 5.12 bC	0.27 ± 0.02 cD
188	52.43 ± 13.65 aA	32.18 ± 10.09 bA	12.16 ± 3.54 cA
195	22.95 ± 6.12 aC	12.44 ± 3.10 bC	3.03 ± 0.87 cB

[1]After the fennel plant was pruned.
[2]Means with the same lower case letter within rows and means with a common upper case letter within columns did not differ significantly in the Student-Newman-Keuls test (P= 0.05).

cal region of the fennel plants was similar to the numbers quantified in the other regions (Table 4). We found more alate aphids in the apical region of the fennel plants at 174, 181, 188 and 195 days after transplanting than at other plant ages (Table 4). In the median region, more alate aphids were found at 167, 174, 181, 188 and 195 days after transplanting (Table 5), whereas in the basal region, more alate aphids were found at 188 days after transplanting (Table 5).

The cropping system affected the number of aphids per plant (apterous: $F_{CS (1, 3)} = 13.75$, $P < 0.0285$; alate: $F_{CS (1, 3)} = 12.43$, $P < 0.0312$), specifically, the number of aphids per plant in the intercropped fennel-cotton system (30.98 apterous aphids/plant and 0.88 alate aphids/plant) was lower than in the fennel system (66.48 apterous aphids/plant and 1.73 alate aphids/plant).

In the fennel system, the apterous aphid population peaked at 153 and 188 days after transplanting (Fig. 2), whereas the alate aphid population peaked at 139 and 174 days after transplanting (Fig. 3). In the intercropped fennel/cotton system, the apterous aphid population peaked at 188 days after transplanting (Fig. 2), and the alate aphid population peaked at 195 days after transplanting (Fig. 3).

From 132 to 188 days after transplanting, the apterous aphid population increased in the fennel cropping system and was fairly variable (Fig. 2). However, in the intercropped fennel-cotton system, apterous aphid population growth was fairly uniform from 160 to 180 days after transplanting (Fig. 2). In both cropping systems, the apterous aphids population began to decrease starting 188 days after transplanting (Fig. 2). Alate aphid population growth was fairly variable in both the monocultured fennel system (132 to 181 days after transplanting) and the intercropped fennel-cotton system (160 to 195 days after transplanting) (Fig. 3). In the fennel system, alate aphid population growth began to decrease at 181 days after transplanting (Fig. 3). However, in the intercropped fennel-cotton system, there was no decrease in alate aphid population growth (Fig. 3).

Between 91.62% and 90.77% of apterous aphids were found on nodes 1 to 12 in the fennel system and on nodes 1 to 10 in the intercropped system (Fig. 4). Similar results were obtained for alate aphids, with 90.46% on nodes 1 to 12 (fennel system) and 91.04% on nodes 1 to 10 (intercropped fennel-cotton system) (Fig. 5).

Because the apterous aphids (Fig. 4) were found mainly on the apical and median nodes of

TABLE 5. NUMBER OF ALATE APHIDS (MEAN ± SD) FOUND ON LEAVES AND UMBELS OF FENNEL PLANTS AS A FUNCTION OF AGE AND VERTCAL PLANT REGION ($F_{R \text{ BY } A (40, 375)} = 1.42$, $P < 0.0513$).

	Plant region[2]		
Plant age (day)[1]	Apical	Median	Basal
55	0.00 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
62	0.00 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
69	0.01 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
76	0.00 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.50 aB
83	0.00 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
90	0.00 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
97	0.00 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
104	0.00 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
111	0.00 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
118	0.07 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
125	0.00 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
132	0.00 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
139	0.22 ± 0.06 aB	0.02 ± 0.00 bC	0.00 ± 0.00 bB
146	0.02 ± 0.00 aC	0.00 ± 0.00 aC	0.00 ± 0.00 aB
153	0.02 ± 0.00 aC	0.00 ± 0.00 aC	0.01 ± 0.00 aB
160	0.18 ± 0.05 aB	0.23 ± 0.02 aBC	0.00 ± 0.00 aB
167	0.25 ± 0.07 bB	0.67 ± 0.07 aAB	0.00 ± 0.00 cB
174	0.84 ± 0.11 aA	0.45 ± 0.05 bAB	0.04 ± 0.00 cB
181	0.97 ± 0.10 aA	0.93 ± 0.09 aA	0.00 ± 0.00 bB
188	0.88 ± 0.09aA	0.47 ± 0.06 bAB	0.32 ± 0.04 bA
195	1.05 ± 0.18 aA	0.65 ± 0.0.07 bA	0.09 ± 0.00 cB

[1]After the fennel plant was pruned.
[2]Means with the same lower case letter within rows and means with a common upper case letter within columns did not differ significantly in the Student-Newman-Keuls test (P= 0.05).

fennel plants in both cropping systems (fennel and intercropped fennel), cubic models better represented the vertical distribution of the aphids in both the fennel cropping system (apterous aphids: $y = 0.652 + 1.436x - 0.195x^2 - 0.005x^3$, $F_{\text{model (3, 19)}} = 19.02$, $R^2 = 0.75$, $P < 0.0001$, $F_{(1, 19)} = 6.80$, $P < 0.0173$; alate aphids: $y = 10.503 - 0.513x$, $F_{\text{model (1, 21)}} = 29.77$, $R^2 = 0.59$, $P < 0.0001$) and the intercropped fennel-cotton system (apterous aphids= $9.364 + 0.784x - 0.169x^2 + 0.005x^3$, $F_{\text{model (3, 19)}} = 34.48$, $R^2 = 0.84$, $P < 0.0001$, $F_{(1, 19)} = 6.09$, $P < 0.0233$ and alate aphids: $y = 11.839 - 0.624x$, $F_{\text{model (1, 21)}} = 43.72$, $R^2 = 0.68$, $P < 0.0001$) (Fig. 4). For the alate aphids, linear models best represented the vertical distribution behavior of the aphids in both the fennel ($y = 10.503 - 0.513x$, $F_{\text{model (1, 21)}} = 29.77$, $R^2 = 0.59$, $P < 0.0001$) and intercropped fennel-cotton ($y = 11.839 - 0.624x$, $F_{\text{model (1, 21)}} = 43.72$, $R^2 = 0.68$, $P < 0.0001$) systems (Fig. 5).

Comparing the linear model coefficients for the fennel and intercropped fennel-cotton systems (SAS Proc Mixed procedure applied to linear coefficient equality), we observed that the vertical distribution pattern for apterous aphids ($t_{(1,989)} = 1.01$, $P > 0.9612$) on the fennel plants did not differ between cropping systems (fennel and fennel intercropped with cotton). Similar behavior was recorded for alate aphids; there was no difference between the 2 systems in the vertical distribution pattern ($t_{(1,989)} = 0.98$, $P > 0.9801$) of the alate aphids on the fennel plants.

Regardless of the cropping system used ($F_{\text{CS by structure (1, 9)}} = 3.83$, $P = 0.0820$), more apterous aphids were found on the umbels (84.61%) than on the leaves (15.39%) of the fennel plants (Fig. 6). Of the apterous aphids found on the umbels, 80.87% were located on umbels produced by apical meristems, and 19.13% were present on umbels produced by lateral meristems (Fig. 6).

We verified that the interaction of the cropping system and the structure of the fennel plant ($F_{\text{CS by structure (1, 9)}} = 1.05$, $P = 0.4186$) was not significant for the percentage of aphids found per plant structure. However, 93.58% of alate aphids were found on the umbels and 6.42% of alate aphids on the fennel leaves (Fig. 7). Of the alate aphids found on the umbels, 87.63% were located on umbels produced by apical meristems, and 12.37% were found on umbels produced by lateral meristems (Fig. 7).

DISCUSSION

Different cropping systems do not affect the aromatic quality of the fennel plant (Carrubba et al. 2008). However, intercropping with different

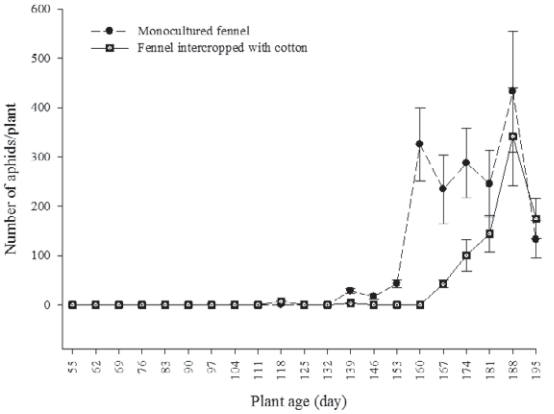

Fig. 2. Dynamics of apterous *Hyadaphis foeniculi* aphids in the fennel monocropping system and in the fennel-cotton intercropping system. Data from 2008 2009 were pooled because the within-in plant distribution of aphids in 2008 was similar to that in 2009. Each data point represents the average number apterous aphids on all the leaves and umbels of 20 fennel plants.

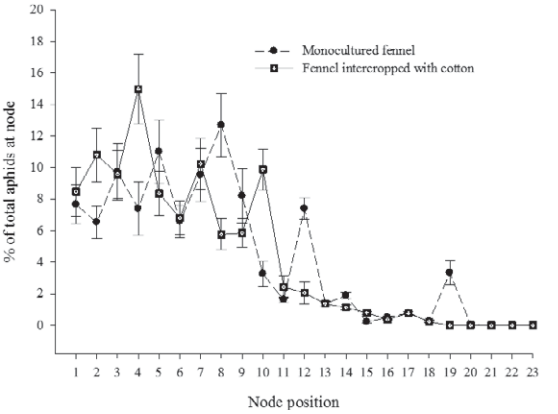

Fig. 4. Vertical distribution (%) of apterous *Hyadaphis foeniculi* aphids at various nodes of fennel plants within the fennel monocropping system ($y = 0.652 + 1.436\,x - 0.195\,x^2 - 0.005\,x^3$, $F_{model\,(3,19)} = 19.02$, $R^2 = 0.75$, $P < 0.0001$, $F_{(1,16)} = 6.80$, $P < 0.0173$), and in the fennel-cotton intercropping system ($y = 9.364 + 0.784\,x - 0.169\,x^2 + 0.005\,x^3$, $F_{model\,(3,19)} = 34.48$, $R^2 = 0.84$, $P < 0.0001$, $F_{(1,19)} = 6.09$, $P < 0.0233$). Node 1 is at the apex and node 23 is closest to the soil surface. Each data point represents the average number apterous aphids on all the leaves and umbels of 420 fennel plants.

species, if implemented properly, can significantly reduce pest problems (Sarker et al. 2007), thus increasing yield and economic returns for the producer (Begum et al. 2010). The results obtained in our study indicate that the cropping system affects the number of aphids per plant (apterous: $F_{S\,(1,3)} = 13.75$, $P < 0.0285$; alate: $F_{S\,(1,3)} = 12.43$, $P < 0.0312$), i.e., the numbers of apterous (27,922) and alate (703) aphids found on the fennel plants were higher than the numbers of apterous (13,012) and alate (369) aphids found on the fennel plants intercropped with naturally colored cotton. Similar results were reported by Amin et al. (2005), Sarker et al. (2007) and Ramalho et al. (2012a, 2012b), who observed fewer pest insects in intercropped systems as compared with monocultures. The fennel intercropped with naturally colored cotton probably benefitted from the physical barrier, the shade provided by the cotton rows (Ramalho et al. 2012a), and consequently from the varia-

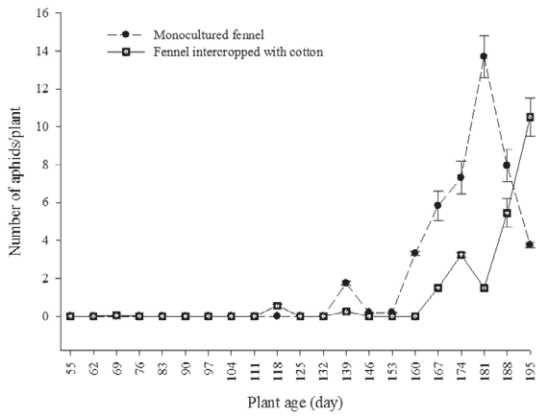

Fig. 3. Dynamics of alate aphids *Hyadaphis foeniculi* in the fennel monocropping system and in the fennel-cotton intercropping system. Data from 2008 2009 were pooled because the within-in plant distribution of aphids in 2008 was similar to that in 2009. Each data point represents the number of average number alate aphids on all the leaves and umbels of 20 fennel plants.

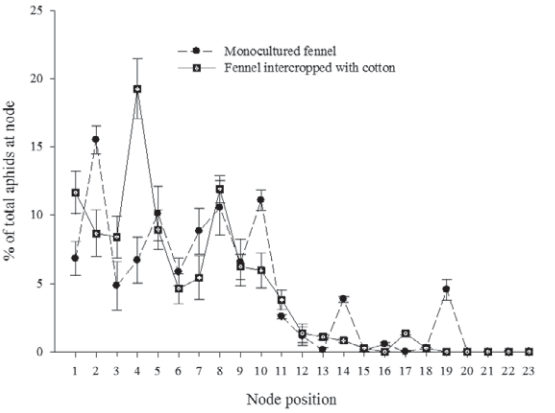

Fig. 5. Vertical distribution (%) of alate *Hyadaphis foeniculi* aphids at various nodes of fennel plants within the fennel monocropping system ($y = 10.503 - 0.513\,x$, $F_{model(1,21)} = 29.77$, $R^2 = 0.59$, $P < 0.0001$) and in the fennel-cotton intercropping system ($y = 11.839 - 0.624\,x$, $F_{model(1,21)} = 43.72$, $R^2 = 0.68$, $P < 0.0001$). Node 1 is at the apex and node 23 is closest to the soil surface. Each data point represents the average of 420 fennel plants.

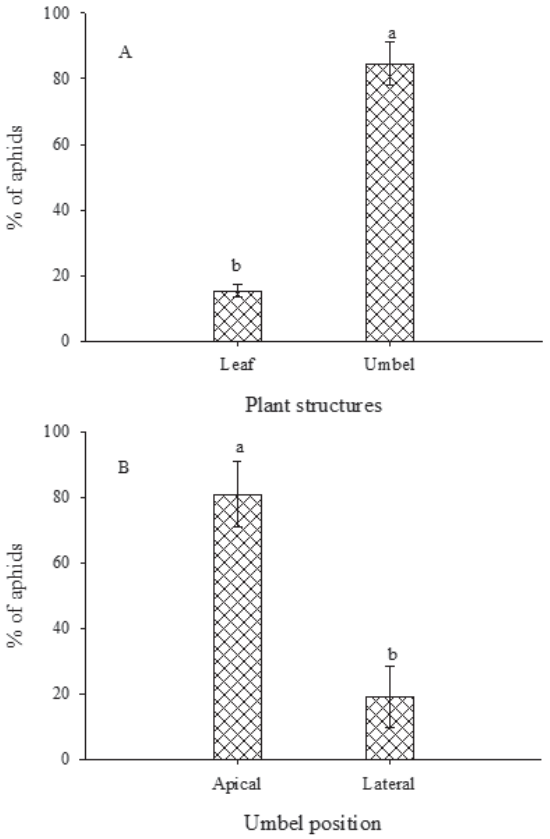

Fig. 6. A (upper panel): Percentage of apterous *Hyadaphis foeniculi* (mean ± SD) per plant structure ($F_{\text{model (6, 9)}} = 17.89$, $P < 0.0002$; $F_{\text{CS (1, 9)}} = 0.02$, $P > 0.9587$; $F_{\text{structure (1, 9)}} = 103.51$, $P < 0.0001$; $F_{\text{CS by structure (1, 9)}} = 3.83$, $P = 0.0820$). B (lower panel): umbel position ($F_{\text{model (6, 9)}} = 14.45$, $P < 0.0004$; $F_{\text{CS (1, 9)}} = 0.03$, $P = 0.9431$; $F_{\text{structure (1, 9)}} = 86.60$, $P < 0.0001$; $F_{\text{CS by structure (1, 9)}} = 0.11$, $P > 0.7450$) in all fennel crops. Different lowercase letters indicate a significant difference between means within each variable.

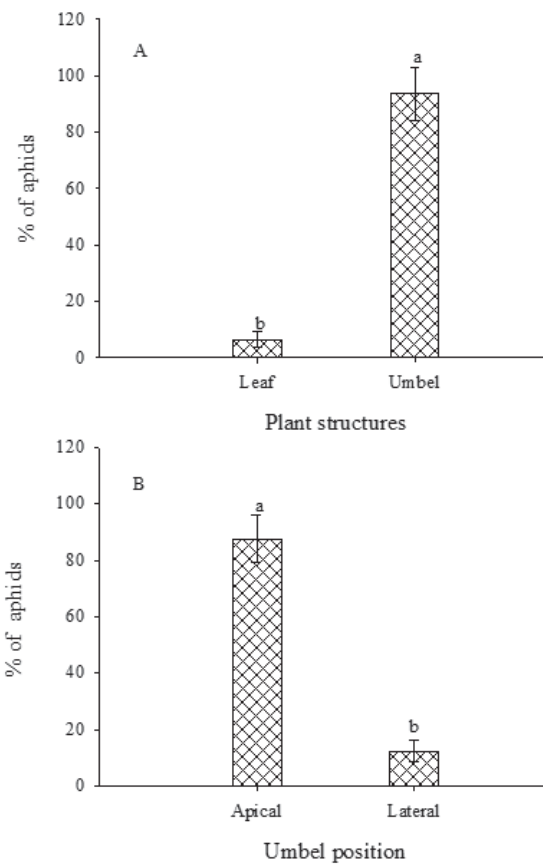

Fig. 7. A: Percentage of alate *Hyadaphis foeniculi* (mean ± SD) per plant structure ($F_{\text{model (6, 9)}} = 73.04$, $P < 0.0001$, $F_{\text{CS(1, 9)}} = 0.01$, $P = 0.9768$, $F_{\text{Structures (1, 9)}} = 437.09$, $P < 0.0001$, $F_{\text{CS by Structure (1, 9)}} = 1.14$, $P = 0.3140$) or B: umbel position ($F_{\text{model (6, 9)}} = 5.21$, $P < 0.0141$, $F_{\text{CS (1, 9)}} = 1.05$, $P = 0.3333$, $F_{\text{Structure (1, 9)}} = 26.35$, $P < 0.0006$, $F_{\text{CS by Structure (1, 9)}} = 1.05$, $P = 0.4186$) in all fennel crops. Different lowercase letters indicate a significant difference between means within each variable.

tion in essential oil content and concentration of monoterpene components that are susceptible to climatic changes, especially temperature, rainfall and light (Aprotosoaie et al. 2010). High concentrations of essential oil and monoterpenes affect the feeding behavior of insect pests (Koul et al. 2008). Other factors that can affect insect behavior in intercropped systems are the diversity of beneficial insects (Ramalho et al. 2012a, 2012b), cropping latitude, fertilization, salinity, plant development or growth retardants, diurnal and annual rhythms, the plant region, the cultivar, the storage of nutrients during different phases and the different parts of the plant studied (Chapin et al 1990; Olle & Bender 2010). Furthermore, the high number of insect families in intercropped systems boosts the diversity index and therefore reduces pests (Amin et al. 2005).

The nutritional composition of fennel cultivars (Koudela & Petříková 2008) varies according to plant age during a given season of the year. According to Trumble (1982) and Koudela & Petříková (2008) plant architecture generally influences aphid densities. Therefore, the interaction between cropping system and plant age (apterous aphids: $F_{\text{SC by A (20, 375)}} = 1.74$; $P < 0.0260$; alate aphids: $F_{\text{SC by A (20, 375)}} = 1.91$; $P < 0.0107$) and between plant age and plant region (apterous aphids: $F_{\text{A by R (40, 375)}} = 2.00$; $P < 0.0005$; alate aphids: $F_{\text{A by R (40, 375)}} = 1.42$; $P < 0.0513$) (Table 1) for the number of aphids found per plant is probably due to the chemical or physical attraction of the plant in terms of the nutrients offered, the wavelength of the light on plant regions at different ages and heights (Trumble 1982; Cividanes & Santos 2003), or even UV radiation throughout the cropping period (Caldwell et al. 2007).

Fennel has phenological characteristics that benefit the environment and help its conservation. Thus, the absence of aphids during the initial crop phase, the higher infestations per plant at 188 (apterous) and 181 (alate) days for the fennel system, and at 188 (apterous) and 195 (alate) days for the intercropped system, taking aphids and the variation in the vertical distribution of apterous and alate aphids between 139 and 195 days after transplanting the fennel plants (Tables 2 and 3) are probably related to climatic conditions (Aprotosoaie et al. 2010). Another factor related to the vertical distribution of the aphids on the plant is the concentration of some carbohydrates in the leaves and sheaths (during the growth and development stage) (Singh et al. 2010), which varies within the plant according to its age (Fernandes et al. 2001; Singh et al. 2010).

The results relating to when the majority of apterous aphids (at 139, 146, 181, 188 and 195 days after transplanting) and alate aphids (at 139, 174 and 195 days after transplanting) were located in the apical region of the fennel plant and when the majority of apterous aphids (at 160 and 167 days after transplanting) and alate aphids (at 167 days after transplanting) were located in the median region, irrespective of the cropping system (Tables 4 and 5), were similar to the results reported by Cividanes & Santos (2003), who also found the majority of aphids in the apical and median regions of spring greens (*Brassica oleracea* var. *acephala* D. C.). They ascribed this behavior to physiological parameters such as leaf area, number of leaves, leaf age, nutrient content, concentration of amino acids and, above all, the concentration of secondary metabolites, particularly glucosinolates such as sinigrin and allylisothiocyanate, which play an important role in aphid feeding preferences. In fennel, the levels of essential oils, fatty acids, sesquiterpenes, coumarins, triterpenoids, tannins, flavonoids, anethole and limonene (Singh et al. 2006; Chowdhury et al. 2009) may be affected by the plant's growth and development (Hendawy & El-Din 2010) and possibly affect the distribution of *H. foeniculi* on the plant parts and regions. The aphids preferred the fennel plants' middle regions for 2 wk during the entire season. Probably this occurred because aphids first inhabit optimal resource locations, and subsequently other locations are filled as the population builds up. Thus, the observed peculiar distribution simply could have been the result of first filling the available apical space, which forced the aphid population to expand downward into the much larger space at the center of the plant.

Studies on the dynamics of *H. foeniculi* indicate that in the fennel system, the apterous and alate aphids showed separate population peaks (Fig. 2), whereas in the intercropped fennel/cotton system, apterous and alate aphids showed only 1 population peak (Fig. 3). Similar results were reported by Resende et al. (2004), who observed only 1 population peak in an intercropped system of spring greens (*B. oleracea* var. Acephala) and rattlebox hemp (*Crotalaria spectabilis* Roth; Fabales: Fabaceae). Aphid population dynamics are not characterized by a defined pattern and are fairly variable throughout the year, particularly when we compare the mechanisms that these insects use; the dynamic can therefore be similar or different (Kindlmann & Dixon 1996).

The losses caused by *H. foeniculi* vary according to climate and cropping system and can reach 80% in a monoculture lacking an ecological management system for aphids (Ramalho et al. 2012b). The decrease in apterous and alate aphid population growth at the end of the cycle in both cropping systems studied and the prevalence of alate aphid population growth in the intercropped fennel/cotton system may be explained by 2 factors. First, after a heavy aphid infestation, some fennel plants in the monoculture system tend to die off, leaving the surviving aphids with fewer nutrients —which aggravates the loss in yield (Ramalho et al. 2012b)—and killing both apterous and alate aphids. Second, intercropped fennel plants have a lower mortality rate and lighter aphid infestations, enabling them to conserve more nutrients, which, in turn, could conserve some alate aphids and natural enemies (Ramalho et al. 2012b). Such surviving alate aphids do not cause significant losses (Ramalho et al. 2012) in part because the fruits (seeds) are soon harvested, i.e., at 195 days after transplanting. Pickett et al. (1992) reported that the individual insect species are sensitive to the chemical aspects of their environment, particularly the host and immediate surroundings. In addition, various aromatic plants contain oleic acid as their main fatty component and aspartic acid, glutamic acid and arginine as their main constituent amino acids, which can change during the plant's growth and development, causing the insect population to rise or fall (Ayad & El-Din 2011).

We observed that 91.62% of apterous aphids were found on nodes 1 to 12 of monocropped fennel and 90.77% of apterous aphids were found on nodes 1 to 10 of intercropped fennel; and the cubic model best represented the insect behavior in this study (Fig. 4). Somewhat similarly 90.46% of alate aphids were found on nodes 1 to 12 of mono cropped fennel and 91.04% of alate aphids were found on nodes 1 to 10 of intercropped fennel, and the linear model best represented the behavior of *H. foeniculi* (Fig. 5). Because each insect species has a qualitative and quantitative requirement for amino acids, the behavior of the aphids may be related to the oligosaccharide or polysaccharide content, which vary according to the ages of the blooms and fruits (Hanny & Elmore 1974).

The spatial distribution of the insects produces characteristic parameters that segregate species and determine the space-time distribution of dynamic changes (Taylor 1984). Thus, when the linear coefficients of the models of the fennel system and intercropped fennel/cotton systems are compared (SAS Proc Mixed procedure applied to linear coefficient equality), the vertical distribution patterns for apterous aphids ($t_{(1,989)}$ = 1.01, P = 0.9612) and alate aphids ($t_{(1,989)}$ = 0.98, P = 0.9801) on the fennel plants do not differ from one cropping system to another, but result in similar characteristics that increase or reduce the pest population density according to plant age (Gonzaga et al. 1991; Cividanes & Yamamoto 2002).

Irrespective of the cropping system, the highest percentages of apterous *H. foeniculi* were found on umbels as opposed to leaves (Fig. 6), with the highest insect concentrations on apical umbels as opposed to lateral umbels (Fig. 7). These findings indicates that the plant fruiting phase attracts this aphid predominantly to its inflorescences (Abramson et al. 2007b) and green fruits, which have higher biomass concentrations (Stefanini et al. 2006). Branches are rarely attacked, and such attacks only occur when the plant is weak or undernourished (Abramson et al. 2007b). Apterous and alate aphid behaviors on fennel probably are related to the concentrations of sugars in the umbels, because in plants of the Apiaceae, fructose and glucose are most concentrated in the inflorescences. A wide variety of insects are attracted to these reproductive structures (Langenberger & Davis 2002). Therefore, the results of our study are extremely important for understanding the vertical and horizontal distribution of *H. foeniculi* on fennel plants in both monocultures and in the fennel-cotton intercropping system; and they should be useful in determining the timing of population peaks, decision making, and implementing controls of this important fennel pest.

Acknowledgments

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