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Broad Mite Effects on Chili Shoot Damage and Yields

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Abstract.- Populations of broad mite and other insect pests on chili shoot, that caused shoot damage and yield were studied from a pesticide free chili field in Kasetsart University, Kamphaeng Saen Campus, Thailand during September to December 2005. Broad mite, *Polyphagotarsonemus latus* was found to be the most common pest collected from young shoots. Mite populations started to increase from the end of September and reached their peak after mid October. The peak densities of broad mite per shoot collected by two different methods were: fresh shoots and shaken from shoots were 7.77±0.24 and 10.32±5.97, respectively. Spearman's correlation analysis revealed that broad mites and thrips were more abundant on shoots with more curled leaves. Downward leaf curling occurred more commonly during the increasing plant damage level in the field. Plants infested by broad mites during the early season frequently had a plant damage level higher than 10% in late season. The more plant damages caused the lower chili yield production. Plant damage level of more than 50% curled shoots resulted in a significant chili yield reduction. Impact of others common pests, thrips and aphid, on chili growth and shoot damage was also discussed.

Keywords: *Polyphagotarsonemus latus*, broad mite, chili, yield damage.

INTRODUCTION

Chili is one of the important economic crops and could be planted in every part of Thailand. It is an important ingredient in most Thai food. Broad mite, *Polyphagotarsonemus latus* Bank, is reported to cause severe chili shoot damage and yield reduction in many areas of the world (Cross, 1979; Gerson, 1992; Cho *et al*., 1996; De Coss-Romero and Peña, 1998; Mossler *et al*., 2006). In growth chamber experiments, damage increases more rapidly with increasing in the number of broad mites and the time of these mites occurred on bell pepper seedlings (Jovicich *et al*., 2004). In 1998, De Coss-Romero and Peña observed that rapid increase of broad mite numbers coincided with the early stage of pepper plants. They found that plant damage caused by broad mite resulted in reduction of chili fruit production and fruit weight in the greenhouse condition. In addition, plants associated with broad mite attack may form the symptoms later due to plant reactions to mites' feeding and putative toxins (Gerson, 1992). Unfortunately, reports on chili damage and yield loss under field condition are still limited. In addition, the composition of arthropods in field conditions is more complex and chili plant damage and yield can possibly be caused by several key pests.

This study is aimed to reveal the relationship of broad mite and other insect pests that caused shoot damage and how the damage affected chili yield under field conditions. Such information would be needed for maximizing control practices.

MATERIALS AND METHODS

Plant and study site

In early September 2005, seven week old "Tavi 64" hot chili seedlings, *Capsicum annuum* L., were transplanted at the Kasetsart University's experimental farm in Nakhon Pathom province, Thailand. Plants were separated at 1 m row width and 45 cm row spacing. Cow manure was placed underneath each plant as fertilizer. A total of 396 seedlings were grown organically without pesticide application and watered by drip irrigation. Three weeks later, liquid organic plant supplement food was sprayed on each plant. A spoonful of 16-16-16 NPK fertilizer was given for each plant a month later or during blossoming stage. Weeds under the chili plants were eliminated by covering rows with black plastic sheets. In addition, weeds between rows were manually removed early in the season.

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Space between each row was then mulched with the rice straw on late October to prevent weed growth until the end of the harvesting period. Plant stages and height were recorded four times during the planting season until all plants produced fruits. The weather conditions were obtained from the Nakhon Pathom's weather station, Kamphaeng Saen, Nakhon Pathom province, Thailand.

Arthropod composition and their population fluctuation

Chili plants were randomly selected every two weeks to be examined for arthropod populations using two methods: collecting fresh young shoots (2 cm in length with 2-3 young leaves) and shoot shaking. Seventy two young shoots were collected at each sampling date during September 26 - December 5, 2005. All samples were kept fresh in zip-lock plastic bags in a refrigerator where all arthropods (especially broad mites, thrips, aphids and predatory mites) were sorted and counted immediately within one day after sampling. This sample set was designated as the fresh young shoot method (F). In addition, 36 young shoots were randomly collected biweekly at each sampling date during October 6 and December 15. The selected young shoots were separately beaten by hand above 12 cm diameter-plastic cups containing 50 ml of 70% ethyl alcohol. The shaken-shoots were also kept fresh in zip-lock plastic bags in a refrigerator before sorting and counting of arthropods on the same day. Moreover, arthropods falling in alcohol were also preserved for later count. Both arthropods found on shoot and in alcohol were then combined for the shaken shoots (S) data. All mites, spiders and insects were counted and grouped as predators or pests. Consequently, population sizes of common arthropod groups were estimated.

Leaf damage index (LDI)

All fully opened leaves in each shoot sample from the fresh young shoot method and the shaken shoot method were measured and graded for curling damage and were categorized into 3 levels; normal (score = 0), less than 50% curl (score = 1) and more than 50% curl (score = 2). Leaf damage index (LDI) of each sample was calculated by summation of outcome from the multiplication of leaf numbers in each damage level by its score, and then divided by the number of all fully opened leaves in that sample. In addition, the position of leaf curls (none, curling upward and curling downward), as well as, roughness of the leaf surface (smooth, rough or wavy) were recorded for each leaf of every shoot. Percentage of leaves curling upward (%CU), downward (%CD) and non-smooth surface (%NS) per number of all fully opened leaves were also calculated for each shoot. Consequently, regardless of sampling methods or sampling date, the relationship of leaf damage parameters and population size of common arthropod groups from each shoot was analyzed. Numbers of shoots showing each type of leaf damage were also calculated separately for percentage of shoot with leaf curling downward and leaf curling upward per total shoot collected from each sampling date.

Plant damage level (PDL)

All plants were observed for proportion of leaf curled to normal leaf, presence of shoot with leaf falling, or new leaf emergence after shoot damage at weekly interval. Plant damage level was categorized into 5 levels: 0 = all shoots with normal leaves, 1 = 1-10% with curled shoots, 2 = 11-50% with curled shoots, 3 = 51-95% with curled shoots, 4 = 96-100% with curled shoots or shoot with leaf falling, 5 = with new leaves emergence from shoot with leaf falling.

Presence of chili pests

One curled shoot was sampled from each plant (total of 396 plants/ sampling date) on October 28, November 14 and December 8, 2005. All curled shoots were kept separately in fresh zip-lock plastic bags in a refrigerator where the chili pests on each sample were checked within one day after sampling.

Chili yield

On November 25-26 and December 20-21, all marketable-sized chili fruits (both damaged and undamaged fruits) from each plant were collected and weighed separately. In addition, undamaged fruits (all or up to 50 grams) were randomly sampled, weighed and counted to estimate fruit weight and the number of fruit produced from each plant.

Data analysis

Descriptive analysis was used to calculate mean and standard error of the arthropod population densities. Bivariate correlations procedure was employed to compute Spearman's rho to estimate how common arthropod densities and leaf damage indices were related as well as the type of damage related to leaf damage indices and the total weight of each related plant at the end of season. In addition, crosstabs among the presence of arthropods were analyzed using chi-square test to understand the association among arthropods, especially between predators and the common pests. All pairs of plant damage level from the same plant were analyzed between two continuously recorded dates using the Wilcoxon signed-ranks method in order to see the progress of curling damage. Then, the plants were divided into two groups depending on the presence of each common pest. Chi-squares in crosstabs procedure were tested for the effect of the presence of any common pests on the distribution of other pests at the same sampling date and the distribution of plant damage. The history of plant damage level, plant height and fruit production were then matched with shoot sampling information from both fresh young shoots and shaken shoots. Bivariate correlations procedure was employed to compute Spearman's rho to estimate how common arthropod densities, leaf damage indices and total weight from each plant were related to history of its' height and plant damage level. Multivariate procedure in general linear model was used to compare plant height, fruit number and yield per plant, among group of plants showing more or less than 50% curled shoots. Within each group of plants, the effect of sampling date was determined by repeated measurement analysis of variances.

RESULTS AND DISCUSSION

Study site characteristics

All plants in this study were in the vegetative stage a month after being transplanted and started to flower. A month later (October 25), 94% of plants were in early fruiting stage, while a few plants were in vegetative and blooming stages. On November 22, fruits from all plants were ready for harvest.

The minimum temperature and maximum humidity of the study site were almost steady in the first three months and the temperatures started getting lower in November and December. The average minimum and maximum temperatures and relative humidity during planting season were 23.3±0.16 to 31.8±0.21ºC and 59.3±0.65 to 93.5±0.17% R.H., respectively. The average rain fall was 4.2±0.99 mm per day and cumulative rain fall was 723.2 mm per season (Fig. 1). The amount of rainfall increased rapidly during September to early November while the plants were in vegetative to blossom stages. Later, during fruiting stage, addition rainfall was negligible till the end of harvesting period. The raining period at the end of November concurred with the new leaves and flowers after first harvest.

Dynamic of broad mite and other chili arthropods

Arthropods associated with curled chili shoots are summarized in Table I. The common pest groups were broad mites (*Polyphagotarsonemus latus*), aphids, and thrips (2.42±1.60, 0.64±0.16 and 0.50±0.04 per shoot, respectively). The thrips species commonly found were *Scirtothrips dosalis* Hood and *Thrips palmi* Karny. Eriophyid mites were the second most common mite pest found in chili young shoot in this season. However, during summer crops, eriophyid might be found in higher densities than this season (unpublished data). The most common predator group was a predatory mite from the family Phytoseiidae (0.13±0.016 per shoot). Berke and Sheih (2000) reported that there were three groups of pests attack chili in Asia; a few species of aphids, broad mite, and thrips (*S. dosalis*) which is similar to our results. However, only broad mite (*P. latus*) and thrips (*S. dosalis*) were brought to attention in the control management research in Asia (Mikunthan and Manjunatha, 2008; George and Giraddi, 2007; George *et al.*, 2007; Jagadeesha and Wali, 2006) and were reported as pests of pepper worldwide (AVRDC, 2001a and b). Bansiddhi and Poonchaisri (1991) found that *S. dosalis* is an important pest in chili and other vegetable crops while *T. palmi* is an important pest of orchid and cotton in Thailand. However, *T. palmi* was also reported as an important pest of chili (or pepper) in Asia, America, Australasia and Europe (Kawai, 1990; Cannon *et al.*, 2007;

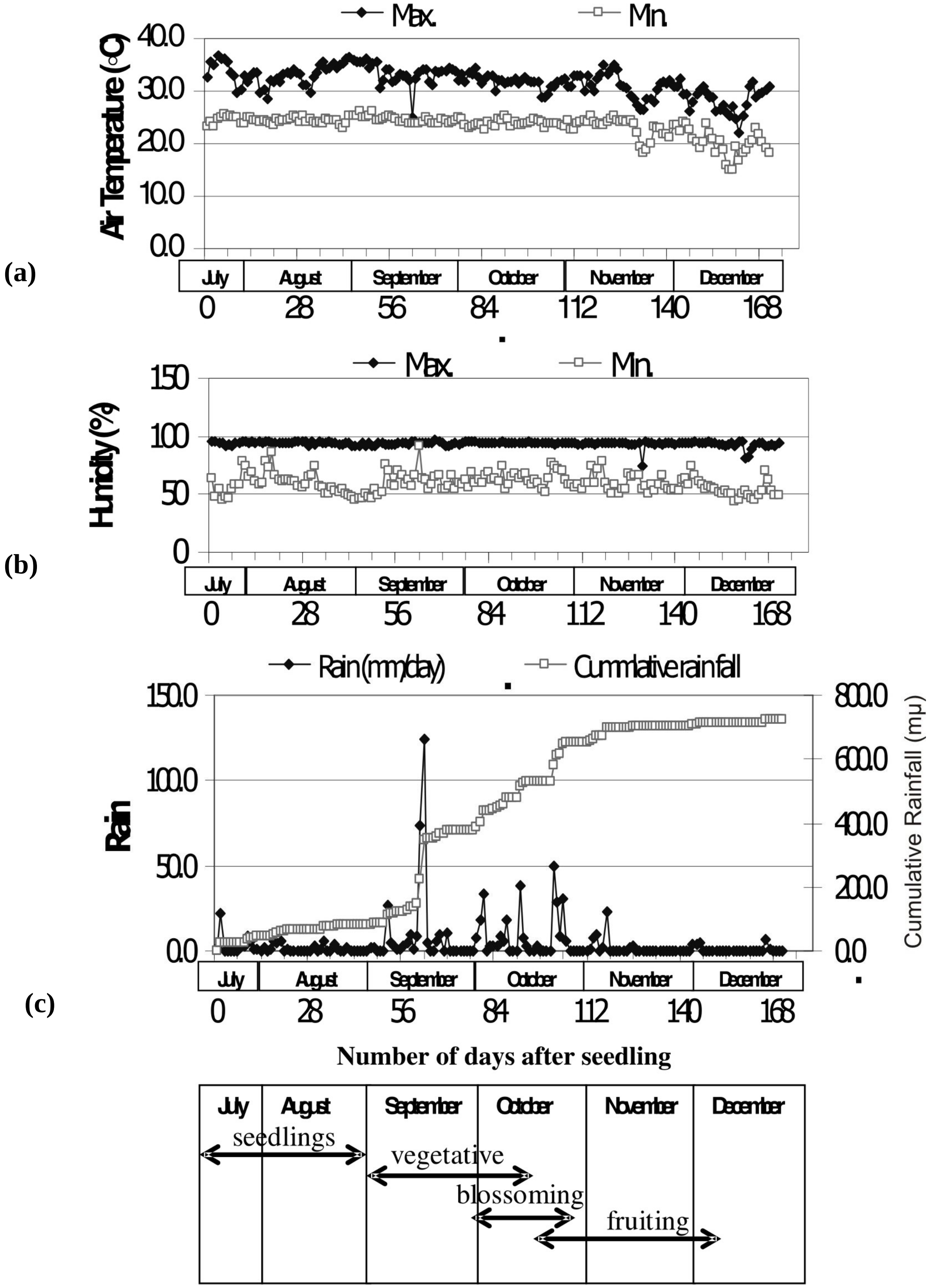

Fig. 1. Maximum-minimum air temperature (a), relative humidity (b) and amount of rain fall per day and cumulative rainfall (c) started from July 14 (Data from the Nakhon Pathom weather station at Kasetsart University, Kamphaeng Saen Campus, Nakhon Pathom, Thailand) and observed plant stages.

Table I.- Total number of arthropods found in all shoot samples (collected by two methods: fresh shoots (F) and shaken shoots (S).

Arthropod groups	Fresh shoots (F)	Shaken shoots (S)	Total
Number of sampling shoots	431*	216	647
Pests			
Acari:	1441	229	
Polyphagotarsonemous latus			1670
Acari: Eriophyidae	18	12	30
Coleoptera: (excepted Coccinellidae and Staphylinidae)	1	9	10
Collembola	0	11	11
Diptera	4	16	20
Heteroptera: Aphididae	447	147	594
Heteroptera: Others	13	19	32
Lepidoptera	5	11	16
Orthoptera	1	4	5
Thysanoptera	110	285	395
Predators			
Acari: Phytoseiidae	60	52	112
Araneae: Spiders	2	54	56
Coleoptera: Coccinellidae	11	15	26
Coleoptera: Staphylinidae	0	1	1
Hymenoptera	6	44	50
Total arthropod numbers	2119	909	3028

* Some samples were lost during storage and transport to the laboratory.

Loomans and Vierbergen, 1997). Later, both *S. dosalis* and *T. palmi* were reported as important thrips found on pepper worldwide (AVRDC, 2001b).

In this study, aphids were the first pests to appear in the chili field in late September (Fig. 2a; F: 4.10±2.14 per shoot). Later, its density per young shoot was reduced to a low level. Then, the broad mite became more abundant and reached its peak after mid October (Fig. 2a; F: 7.77±0.24 per shoot, and Fig. 2b; S: 10.32±5.97 per shoot), when chili plants were in vegetative to early fruiting stages. After late October (during fruiting stage), broad mite population declined while the number of thrips started to increase (Fig. 2). Finally, in early December (during late fruiting stage and after first harvest) thrips and aphids increased in numbers to peak level (Fig. 2b; S: thrips = 2.83±0.65, aphids = 1.67±0.55 per shoot), while broad mite numbers gradually reduced to a minimum (Fig. 2).

Broad mites were highest on the first two sampling dates (early fruiting stages) than the last date (late fruiting stage) while inverse patterns were found for aphids and thrips (broad mites: 114, 173 and 12; aphids: 2, 32 and 115; thrips: 19, 35 and 117). The results agreed with the densities of pests observed in the crop.

Population fluctuation patterns may be different between the years and places. The pattern of population fluctuation of broad mites in this study was similar to the results of Weintraub *et al.* (2003) where the pepper plants were transplanted about the same time of the year (September 2). Broad mites increased until peaking during mid October – mid November and gradually declining in the later season. This fluctuation is probably due to physical factors such as the amount of rainfall and/or biological factors such as the changing of plant stage as well as the presence of other arthropods or interactions between the different factors.

As shown in this study, increasing broad mite density was related to the time and cumulative amount of rainfall during September till mid October. Then, the population fell drastically due to low additional rainfall and cooler temperature starting in late November till the end of season. In contrast, the thrips population from the shaken shoots was low during the rainy period and started to increase in number with less rainfall after mid November (Fig. 1c). Thus, broad mite and thrips respond to these physical factors in different ways.

Palumbo *et al.* (2002) reported the successful suppression of thrips populations using overhead sprinkler to simulate rainfall in romaine lettuce. *S. dosalis* was also reported to cause more damage on leaves, buds or flowers especially during the dry seasons (November – April) in Thailand (Bansiddhi and Poonchaisri, 1991). In contrast, Leite *et al.* (2003) found that densities of mite pests on eggplant positively correlated with total rainfall. Hence, the rain may dislodge thrips from plants but not broad mite. Our results agreed with Peña (1990) who reported the density of broad mites to be high during the rainy period in spring and summer. Phompanjai *et al.* (2005) planted sesame at different times of the year and indicated that if the plants emerged later in the rainy season, a higher infestation broad mites was observed at the peak population density. However, they found broad mite on sesame at any of the planting dates. The peak population occurred 35-42 days after plant emergence. Additional rainfall after the population peak was reached in the season, could not prevent a reduction in mites both in Pena's (1990) and our studies as well. This suggested that though the rain might not cause the negative impact on broad mites' density, it was not the major factor to directly promote their population growth. However, the rain might indirectly manipulate broad mites via the impact on the other biological factors related to them such as host plant suitability.

Our results indicated that broad mite infestation period occurred during vegetative to early fruiting stage under field conditions. This was in agreement with Coss-Romero and Peña (1998) for the population fluctuation of chili pests under greenhouse conditions. Broad mite population also increased from the vegetative to the flowering stages and reached the highest peak in young pod stage in sesame (Phompanjai *et al.*, 2005). Jovicich *et al.* (2004) stated that the population growth of broad mites was more rapid on bell pepper seedlings since there were more leaves available to feed upon than in the cotyledon stage. However, mite populations declined after partly due to plant age, as in the case of young cucumber leaves that were preferred by broad mites over older cucumber leaves (Alagarmalai *et al.*, 2009), but largely because the plants were injured by the mites as in the case of *Tetranychus urticae* Koch feeding on beans (Nachman and Zemek, 2002). In addition, the seasonal change in leaf quality might be responsible for population reduction as in *Tetranychus kanzawai* Kishida populaions on hydrangea (Gotoh and Gomi, 2000).

The presence of predators and other pests could have also induced broad mite and thrips population fluctuations. The obvious result in this study was the number of predatory mites fluctuated alternately with pest densities collected in fresh shoots (Fig. 2a). The number of predatory mites started to increase in mid-late October, following the increasing numbers of broad mites and thrips on the shoot (Fig. 2a; Oct 10-24 and Fig. 2b; Oct 20–Nov 3). Then the predator's number reached its peak at mid November, when the numbers of both pests did not increase (Fig. 2a; Oct 24-Nov 21 and Fig. 2b; Nov 3-17). After that, the predatory mite number fluctuated alternately with the change of thrips and aphid population (Fig. 2a; Nov 21-Dec 5 and Fig 2b; Dec 1-15). The results showed a delay response of predator number to their prey. This incident was also found in some other predator-mite systems, such as predatory mites - *T. kanzawai* (Gotoh and Gomi, 2000).

Relationship among arthropods

The crosstabs between the presence of thrips, aphids and broad mites on the same plant as analyzed by chi-square test did not show any strong association between these pests. However, with one exception (on November 14), when the aphid densities were very low, the proportion of plants with aphids on the same shoot with broad mites was significantly less than those shoots with aphids alone (Pearson's Chi-Square: p = 0.026). This result agreed with the negative Spearman's rho correlation coefficient between aphids and broad mites (Table II). This result suggested that broad mites might avoid competition with aphids, or vice versa. However, we may need to study in more detail in the laboratory and record data more frequent in the field to observe the interference between these two pests in early transplantation.

In contrast, relationship between thrips and aphids was not similar to that of aphids and broad mites. Thrips densities were positively related with aphid densities, especially in late season (Table II, Fig. 2). The crosstabs suggested that the presence of thrips and aphids on plant at any sampling date did not depend on each other (Pearson's Chi-Square: p = 0.690, p = 0.158, p = 0.996). In other words, thrips tended to stay on any plants regardless of the presence of aphids and vice versa. Thrips and aphids could be found on separate plants or stay together on the same plants. However, if they were found on the same plant, the higher the aphid densities, the higher the thrips densities or vice versa. The possibility of a positive relationship among the pest species could occur via the

Table II.- **Spearman's rho correlation coefficient among common arthropods from all sampling units and correlation between leaf damage indices and arthropods (n=647).**

	Broad mites	Thrips	Predatory mites	Leaf damage index	Total weight
Aphids	-0.082*	0.211***	0.014	0.035--	0.072
Broad mites		-0.060	-0.066	0.136***	0.070
Thrips			0.121***	0.209***	-0.039
Predatory mites				0.106**	-0.069
Leaf damage index					-0.048

* and ** and *** Correlation are significant at the 0.05 and 0.01 and 0.005 level (2-tailed), respectively.

Table III.- **Spearman's rho correlation coefficient between history of the plant (plant height (PH) and plant damage level (PDL)) and common pests, leaf damage indices that were sampled from that plant from all sampling units and total fruit weight of that plant (n=647).**

	Broad mites	Thrips	Aphids	Leaf damage index	Total weight
PH on Sep 27	-0.040	-0.005	-0.046	-0.019	0.004
PH on Oct 25	-0.121**	0.013	-0.095*	-0.045	0.022
PH on Nov 22	-0.138***	0.024	-0.048	-0.025	0.092*
PDL on Sep 27	-0.032	-0.035	-0.064	0.045	-0.091*
PDL on Oct 04	-0.064	-0.039	-0.027	0.065	-0.137***
PDL on Oct 11	-0.100*	0.028	0.035	0.041	-0.351***
PDL on Oct 17	0.028	0.011	-0.034	0.077*	-0.216***
PDL on Oct 25	-0.080*	0.043	-0.038	-0.009	-0.132***
PDL on Nov 01	-0.011	0.032	-0.046	0.004	-0.129***
PDL on Nov 07	-0.019	0.033	-0.040	-0.017	-0.164***
PDL on Nov 15	-0.014	0.025	-0.035	-0.011	-0.172***
PDL on Nov 22	-0.045	0.000	0.000	0.005	-0.168***
PDL on Nov 29	0.170**	-0.004	-0.055	0.122**	-0.121***
PDL on Dec 06	0.122**	0.036	0.036	0.076	-0.343***
PDL on Dec 13	0.122***	0.037	0.054	0.065	-0.329***

* and ** and *** Correlation are significant at the 0.05 and 0.005 and 0.001 level (2-tailed), respectively.

cooperative relationship or they both were response to the same physical environments or the same plant quality. The plant with high qualities seemed to support more herbivores. Although herbivores on plants competed with each other for food, some could tolerate the cost of being together to avoid predators such as the relationship between the thrips and spider mites, where thrips were more abundant on plants with spider mites in the presence of predators (Magalhaes *et al*., 2007).

Interestingly, during early season to mid season while predatory mites (Phytoseiid mite) were still low in number, thrips densities were positively related with predatory mites densities when samples were taken from the same shoot (Table II). Predatory mites could be found in a higher density with more prey densities. This suggested the aggregation response of predators on thrips when they were on the same plants. High populations of *P. persimilis* were also found on cucumber leaves with more *T. urticae* (Nachman, 2006). Although, some omnivore thrips may cause the negative impact on predator mites via feeding on mite eggs during low food quality conditions (Janssen *et al*., 2003), those omnivore thrips may have a minimum impact in this study since the omnivore species was not detected in the field.

Relationship between arthropods and leaf damage

The positive Spearman’s rho correlation coefficient (*P<0.001*) between leaf damage index and percentage of leaves that had each type of leaf damage, suggested that the damage occurred on young leaves partly described by a roughly surface

(R^2=0.936), curling down (R^2=0.565) and curling up (R^2=0.510). However, from all 647 collected shoots in both fresh young shoots and shaken-shoots, only 23% of all shoots were not damaged and had no arthropods on shoots, especially in early season. Moreover, 5% and 9% of all shoots with no signs of leaf damage had 1-250 broad mites and 1-9 thrips per undamaged shoot, respectively. While 54% of shoots had one type or a combination of some or all types of curling damage on their young leaves, 62% of shoots had at least one type of arthropod on some young leaves. These results indicated that the damage did not appear right away after the pests arrived. The damage appeared locally and probably resulting from cumulative feeding damage. The damage was still on the leaves, even though the pest was not there in later season.

Densities of broad mites and thrips as well as predatory mites were positively related with leaf damage index (LDI) (Table II). This result suggested that the higher density of both pests, but not aphids, could cause higher leaf curling level. Broad mites could be responsible for the damage on the young leaves as indicated by the higher portion of curling downward shoots concurring with duration of first peak of broad mites density in early season till early fruiting period, as well as, duration of new shoot emerged after first harvested date (Fig. 3). However, thrips also produced more damage on the shoot after broad mites when the leaves were getting older which suggested by a higher percentage of curling upward shoot occurred during only in fruiting period (Fig. 3) when thrips were abundance (Fig. 2). These results agreed with known symptoms of broad mites and thrips on chili leaves, curled downward and curled upward, respectively (AVRDC, 2001a,b) and pest fluctuations reported above. Other studies did not look at the relationship of the number of broad mites with the level of leaf damage directly, but they compared leaf damage of plants with or without broad mite (control treatment). Their results suggested the presence of broad mites especially on the younger leaves could cause significantly higher leaf damage on pepper (Coss-Romero and Peña, 1998) and cucumber (Grinberg *et al.*, 2005). Jovicich *et al.* (2004) also reported that the earlier colonization of broad mites on the plant resulted in higher broad mite numbers on 38 day old pepper seedlings as well as more reduction of leaf area and water content as compared with the uninfested plant of the same age. Thrips (*S. dorsalis*) also caused damage in Thailand to leaves, but more on flowers and young fruit (Bansiddhi and Poonchaisri, 1991). *S. dorsalis* may have also caused continuing chili leaf curl damage since they were reported processing strong viruliferous behavior for viruses (Jha *et al.*, 2010).

Interestingly, more predatory mites were found on shoots with the higher leaf damage suggesting that they might find this habitat suitable for food. This result indirectly agreed with the number of predatory mites positively related to thrips densities shown above. Nachman (2006) suggested that predator mites (*P. persimilis*) tended to aggregate on leaves with an abundance of their prey (*T. urticae*). A similar result was found in our studies, both thrips and broad mites served as prey for the predatory mite found in this study. However, the absence of relationship between the number of predatory mites and broad mites was probably due to the more successful search for the broad mite than thrips, subsequently, no or fewer broad mites could be observed in the samples. Thus, sampling techniques may need to be considered in order to quantify this relationship in the future studies.

Plant damage level and it's relation with arthropod pests

Wilcoxon signed-ranks test suggested that a significant increase in plant damage level occurred during vegetative and blossoming stages (Figs. 1 and 3b). More than 90% of chili plants had no sign of pest infestation within four weeks after being transplanted (September 27). Plant damage level increased slowly in the first three weeks, when approximately 50% of plants had some damage at level 1 or more. Then, plant damage dramatically increased from October 17 to October 25, the same period as the peak of seasonal rain fall (Fig. 1), peaks of broad mite densities in all sampling methods (Fig. 2) and the first peak of percentage of shoot with leaf curling downward (Fig. 3a). This resulted in more than 90% of the plant damage and 58% of plants with curled shoots at level 2 (11-50%

curled shoots) on October 25. Later, the average plant damage level slightly increased (Fig. 3b) at the same period as the peak percentage of shoots with leaf curling upward, but a decline in the percentage of shoots with leaves curling downward (Fig. 3a). The level of plant damage increased from 1 to 2 or from 2 to 3-5, and about 8% of plants were damaged greater than 50% during this first peak of shoot curling damage.

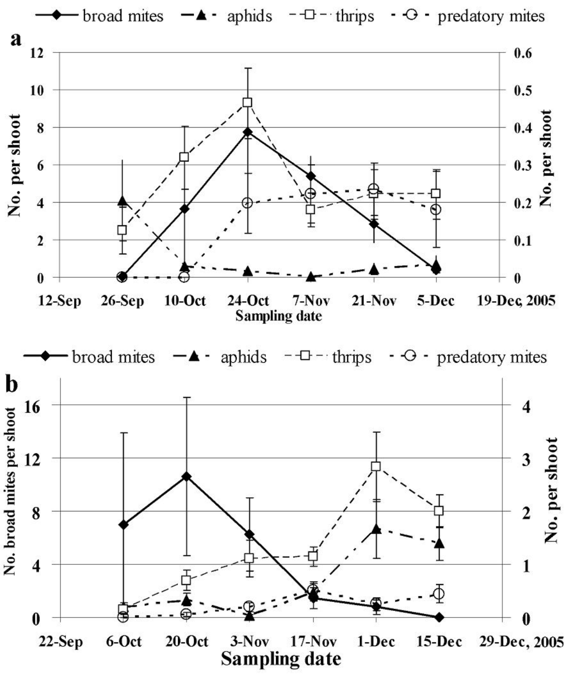

Fig. 2. (a) Population fluctuation of broad mites, aphids (values showed on left axis), thrips and predatory mites (values showed on right axis) sampling by fresh shoots (F) during September 26 to December 5; (b) Population fluctuation of thrips, aphids, predatory mites (values showed on right axis) and broad mites (values showed on left axis) sampling by shaken shoots (S) during October 6 to December 15.

During November 8-15, when the plants were in late fruiting stages (fruits almost ready to harvest), plant damage level did not change, but continued to recover (Fig. 3). In this recovery period (November 17-22), the number of broad mite was reduced while thrips and aphids were in low numbers (Fig. 2). Although in some plants, the damage level increased from level 2 to 3-5, but most plants produced new young shoots and the thrips might been washed off the plant after a light rain fell in November 3-7 and November 15-16 (Fig. 1). This phenomenon might result in less than 50% of shoot sampling in this period with curling damage (Fig. 3a) and also resulted in low percentages of curled shoots on each plant, and plant damage level then reduced from level 2 to 1.

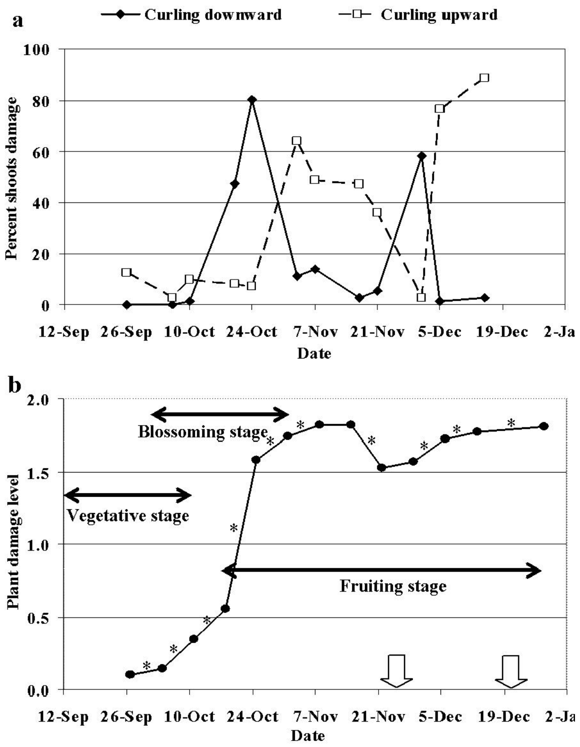

Fig. 3. (a) Percentage of shoot damage per all sampling shoots collected in each sampling date, comparing between curling downward and curling upward; (b) average of plant damage level (*Wilcoxon signed-ranks is significant at the 0.002 level (2-tailed)), arrows indicated two harvested dates.

After the fruit was harvested on November 25-26, more new shoots developed at the same time. Plant damage levels gradually increased during the rising period of pest numbers as well as the time that pests developed on the plants (Figs. 2 and 3). More shoots with leaf curl downward were also detected at first sampling and followed by a peak of more shoots with leaf curl upward (Fig. 3a). Plant damage level significantly increased again a few weeks later, as recovering plants had a higher plant damage level again. This was probably due to the impact of broad mite feeding on new young leaves, even at low population levels (Fig. 3a), followed by peak thrips and aphid populations in late season (Fig. 2b). Once the shoots reached the mature stage with no addition of young leaves or increase in the number of predatory mites in late fruit stage, the damage did not increase much.

The crosstabs between the presence of pests and plant curling damage level (PDL) suggested that the distribution of PDL differed among plants with and without broad mites in some dates, but not among plants with and without other pests (data not shown). The results confirmed the above findings (Figs. 2, 3) that a few weeks before each harvested date, thrips and aphids might become pests and could cause different types of damage and/or cause more leaf curling damage on some plants and broad mites could cause leaf falling after severe damage. Plants with broad mites (October 28, (n = 114 plants) and November 14, (n=173 plants)) resulted in a higher frequency of plants with more than 10% curling damage. Plants with a damage level higher than 50% shoot curling (level 3 to 5) were observed on plants infested with a higher frequency of broad mites than the uninfested ones. The broad mite was the most important factor causing damage to this crop because they were found on more plants than other pests in early season. In addition, plants with broad mites from previous stages tended to show higher plant damage levels during the fruiting stage. However, on December 8, broad mites were observed on only 12 low-damage plants that were recently infested, or had been damaged to the highest level and recovered to a low level of plant damage. The results suggested that broad mites may cause higher plant curling damage, but they tended to leave the high leaf-curling damage plants and were found only on plants that had better shoot quality or less damage.

The highly significant Spearman's rho correlation coefficient ($P<0.005$) between broad mite density on one sampling shoot of each plant and the history of that plant (plant height and plant damage level) confirmed the negative impact of broad mite on chili plant (Table III), but not the other two pests. The higher the broad mite density during the season on a shoot from the plant, the height of that plant was lessened when measured in mid and late season and the higher plant damage level after first harvested date. The non ($P>0.05$) or marginally ($P<0.05$) significant negative Spearman's rho correlation coefficient of the same test with plant damage level early in the season (while broad mite was still high densities) suggested the same result as the above crosstab analysis that, during the rising period of the broad mite population, the broad mites tended to grow and had a higher density on plants that showed lower damage levels and left plants that had high damage levels. However, a higher density of broad mite could cause leaves to fall after severe damage and resulted in higher plant damage level later in the season when its' population was in decline. The cumulative increase in plant damage level overtime may also indicate the cumulative impact of the pest toxins or from diseases carried by pests as suggested by Gerson (1992) and Jha (2010) who provided some evidence from the literature for chili leaf curl disease being associated with broad mites and thrips (*S. dorsalis*).

Effect of plant damage on height and yields

A direct relationship between pest density per shoot sampling or leaf damage index was not related to the total weight (Tables II and III). However, broad mites may have caused on indirect response for 1) high leaf damage index during the abundance of fresh young shoot; 2) plant height and 3) the plant damage level during harvesting period as discussed above. Then, both diverse plant damage level and leaf damage index during the rising period of leaves curling downward on shoots may have allowed a positive relationship between the leaf damage index and plant damage levels (Table III). Therefore, the cumulative effect of damage on several shoots of a plant as indicated by plant damage level, is a better way to describe the impact of pests and leaf damage on yield. The negative Spearman's rho correlation coefficient between plant damage level of all dates and total weight in later season suggested that the chili productions was reduced when plants had high damage levels (Table III).

Chili plants were then divided into 2 groups depending on the history of plant being damaged, level 3 damage or less damage. The plants with the history of being damaged to the least a level 3 was 11.4% of the chili plants in the field. The average height of plants significantly increased over time (*P<0.001*). However, plant height at different damage levels did not differ statistically (Fig. 4a). Yet, the total yield and number of fruit produced per plant from our chili plants with more than 50% shoot curling damage were significantly less than those from plants with less than 50% shoot curling damage (Fig. 4b). Different collecting dates showed no effect on the impact of damage on any variables. This result suggested that the plants that have more than 50% cured shoot (PDL > level 3) did not show the plant stunting as compared with plants that always had less damage than 50% curled shoot. Bell pepper seedling stem length as well as the height of pepper plant at vegetative stage through early fruiting stage was also reduced in size with the presence of broad mites (Coss-Romero and Peña, 1998; Jovicich *et al.*, 2004). If broad mites just infested 5 days before measuring seedling's stem length or just started infestation in late fruiting stage, the height also induced, but only about 10% and 5%, respectively (Coss-Romero and Peña, 1998; Jovicich *et al.*, 2004). The plant stunting might be due to high broad mite infestation or the time of infestation needed to be early enough in the growing period to cause the damage. As in our studies, broad mites started to colonize on chili plants at 3-4 weeks after planting (start of the bloomming stage), before that period they might be controlled by predators as well as the other factors in the field. The impact of naturally occurring predators also caused a low level at the peak of broad mite infestation in leafy vegetables in Benin (Adango *et al.*, 2007). As the result, the high level damage plants in our studies did not significantly show the stunt symptoms. However, the cumulative effects of damage on a plant greater than level 3 could reduce yields similarly to those in other studies (Coss-Romero and Peña, 1998; Cho, 1996).

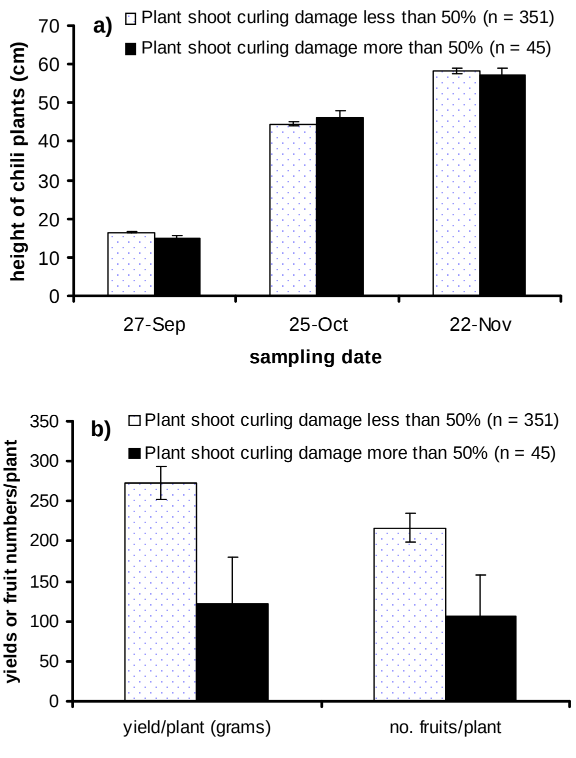

Fig. 4. Mean and standard error of (a) height of plants, and (b) weights and fruit numbers produced per plant compared between plants with (black bar) or without (open bar) shoot curling damage level equal to or greater than 3 at least once before first harvesting date. * Univariate analysis of varience is significant at 0.05 level (2-tailed).

Higher aphid numbers could also have resulted in shorter chili plant height at mid season (Table III). Thus, aphids might have caused some impact on chili plant in a different manner other than causing leaf curling damage on young shoot. However, the impact of aphids on chili production in our studies could be minimal since there was no significant relationship of plant height at mid season on total weight (Table III: $P>0.05$), while there was in late season ($P<0.05$). Lepidopteran pests also damaged chili fruits in our studies. However, we did not design experiments for sampling those finding. The more complex system of pest damage on different parts of chili plants that affect chili production still remains to discover.

CONCLUSIONS

The broad mite is the most common pest infesting chili plants in rainy season during the vegetative to early fruiting stages and caused leaf curling damage on chili plants. However, very few plants had shoot damage more than 50% which might have resulted in the reduction of fruit and total yield production. Thrips also played some role in plant damage in the late season when there was no rain. Pest population fluctuations might respond to the presence of predatory mites in the field which kept the pest infestation at a low level.

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