Major pests of African indigenous vegetables in Tanzania and the effects of plant nutrition on spider mite management

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Abstract

Pest status of insect pests is dynamic. In East Africa, there is scanty information on pests and natural enemy species of common African Indigenous Vegetables (AIVs). To determine the identity and distribution of pests and natural enemies in amaranth, African nightshade and Ethiopian kale as well as pest damage levels, a survey was carried out in eight regions of Tanzania. Lepidopteran species were the main pests of amaranth causing 12.8% damage in the dry season and 10.8% in the wet season. The most damaging lepidopteran species were *S. recurvalis*, *U. ferrugalis,* and *S. litorralis*. Hemipterans, *A. fabae, A. crassivora,* and *M. persicae* caused 9.5% and 8.5% in the dry and wet seasons respectively. *Tetranychus evansi* and *Tetranychus urticae* (Acari) were the main pests of African nightshades causing 11%, twice the damage caused by hemipteran mainly aphids (5%) and three times that of coleopteran mainly beetles (3%). In Ethiopian kale, aphids *Brevicoryne brassicae* and *Myzus persicae* (Hemipterans) were the most damaging pests causing 30% and 16% leaf damage during the dry and wet season respectively. Hymenopteran species were the most abundant natural enemy species with aphid parasitoid *Aphidius colemani* in all three crops and *Diaeretiella rapae* in Ethiopian kale. Coccinellids beetles were present in all crops.

Based on the survey findings, further studies were carried out to determine the effects of fertilizer and water regimes on host selection, population and damage of *Tetranychus evansi* on *Solanum scrabrum*. The effects of these regimes on leaf alkaloid content were also evaluated. When fertilizer and water regimes experimentally varied, mite population and leaf damage increased with a decrease in soil moisture and nutrient with 35% leaf damage observed in the highest regime and 73% in the lowest. In addition, alkaloid content was highest in the high moisture and low fertilizer regimes and low in all regimes with the lowest moisture level. The alkaloid content of the tested plants negative correlated with mite population at extreme regimes.

Knowledge generated from this study will inform farmers and extension service providers on the major pests of these vegetables and help in prioritizing pest management resources. African nightshades farmers ought to ensure crops are well watered and receive adequate fertilizer particularly during the dry season when the crop is mainly grown under irrigation. This could suppress red spider mite populations and increase yields.

Key words: Vegetables, plant nutrition, insect pests

Zusammenfassung

Der Schädlingsstatus von Schadinsekten ist dynamisch. In Ostafrika gibt es nur spärliche Informationen über Schädlinge und natürliche Feindarten der häufigen afrikanischen einheimischen Gemüsearten (AIV). Um die Identität und Verbreitung von Schädlingen und natürlichen Feinden bei Amarant, Afrikanischem Nachtschatten und Äthiopischem Grünkohl sowie den Grad der Schädlingsschädigung zu bestimmen, wurde eine Erhebung in acht Regionen Tansanias durchgeführt. Lepidopterenarten waren die Hauptschädlinge des Amarant, die in der Trockenzeit 12,8% und in der Regenzeit 10,8% der Schäden verursachten. Die schädlichsten Lepidopteren-Arten waren *S. recurvalis*, *U. ferrugalis* und *S. litorralis*. Hemipterans, *A. fabae*, *A. crassivora* und *M. persicae* verursachten 9,5% bzw. 8,5% in der Trockenzeit und 8,5% in der Regenzeit. *Tetranychus evansi* und *Tetranychus urticae* (Acari) waren die Hauptschädlinge der afrikanischen Nachtschattengewächse und verursachten 11%, doppelt so viel Schaden wie Hemipteran hauptsächlich Blattläuse (5%) und dreimal so viel wie Coleopteran hauptsächlich Käfer (3%). Im äthiopischen Grünkohl waren die Blattläuse *Brevicoryne brassicae* und *Myzus persicae* (Hemipterans) die schädlichsten Schädlinge, die während der Trocken- und Regenzeit 30% bzw. 16% Blattschäden verursachten. Hautflügler-Arten waren die häufigsten natürlichen Feinde mit dem Blattlausparasitoiden *Aphidius colemani* in allen drei Kulturen und *Diaeretiella rapae* im Äthiopischen Grünkohl. Coccinellids-Käfer kamen in allen Kulturen vor.

Auf der Grundlage der Umfrageergebnisse wurden weitere Studien durchgeführt, um die Auswirkungen von Dünger- und Wasserregimen auf die Wirtsauswahl, die Population und die Schädigung von *Tetranychus evansi* auf *Solanum scrabrum* zu bestimmen. Die Auswirkungen dieser Regimes auf den Blattalkaloidgehalt wurden ebenfalls bewertet. Wenn die Dünger- und Wasserregimes experimentell variierten, nahmen die Milbenpopulation und die Blattschäden zu, während die Bodenfeuchtigkeit und der Nährstoffgehalt abnahmen. Beim höchsten Regime wurden 35% und beim niedrigsten Regime 73% Blattschäden beobachtet. Darüber hinaus war der Alkaloidgehalt in den Regimen mit hoher Feuchtigkeit und niedrigem Düngergehalt am höchsten und in allen Regimen mit dem niedrigsten Feuchtigkeitsgehalt am niedrigsten. Der Alkaloid-Gehalt der getesteten Pflanzen korrelierte negativ mit der Milbenpopulation bei extremen Regimen.

Das aus dieser Studie gewonnene Wissen wird Landwirte und Anbieter von Beratungsdiensten über die wichtigsten Schädlinge dieser Gemüsearten informieren und bei der Priorisierung von Schädlingsbekämpfungsressourcen helfen. Afrikanische Nachtschattenbauern sollten sicherstellen, dass die Nutzpflanzen gut bewässert werden und ausreichend Dünger erhalten, insbesondere während der Trockenzeit, wenn die Ernte hauptsächlich unter Bewässerung angebaut wird. Dies könnte die Spinnmilbenpopulationen unterdrücken und die Erträge steigern.

Schlüsselwörter: Gemüse, Pflanzenernährung, Insektenschädlinge

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List of abbreviations

AIVs:	African Indigenous Vegetables
ANOVA:	Analysis of Variance
AVRDC:	World Vegetable Center
FAO:	Food and Agricultural Organisation
masl:	Metres above see level

. General introduction

1.1 Importance of African Indigenous Vegetables

African Indigenous Vegetables (AIVs) are gaining popularity in East Africa communities. These vegetables have appealed to the consumers and development agencies due to their potential to improve nutrition and thus livelihoods for low-income households (Muriithi et al., 2003). Malnutrition is considered the most serious health problem in the world and more so, in sub-Saharan Africa (FAO, 2012). AIVs are rich in nutrients (Ochieng et al. 2007) and are reported to medicinal properties (Odongo et al., 2017) and can greatly improve dietary diversity. Although agriculture is the main source of livelihoods for most East Africa communities, most staples crops are rich in carbohydrates but limited vitamins and minerals (Ochieng et al, 2016). The agronomic traits of AIVs make them better adapted to local conditions and have higher nutrients compared to common exotic leafy vegetables (Shackleton et al. 2009; Fordham & Hadley 2003). Besides, AIVs are known to have short production time, require minimal production inputs, and are easily sold through local markets. Consequently, the production of AIVs especially in the urban and peri-urban settings has become a viable income-generating activity for poor households (Muhanji *et al*, 2011). Common indigenous vegetables grown in Tanzania include Amaranthus (*Amaranthus spp*.), African nightshades (*Solanum scabrum/villosum/americanum*), African eggplant (*Solanum aethiopicum*), spider plant (*Cleome gynandra*), cassava leaves (*Manihot spp*), cowpeas (*Vigna unguiculata*), Ethiopian kale (*Brasssica carinata*), Pumpkin leaves (*Cucurbita pepo*), and sweet potato leaves (*Ipomoea batata*) (Keding et al. 2007).

1.2 Amaranth and associated pests

There are about 70 species in the genus Amaranthus (*Amaranthus spp*) and among these, 40 species are thought to have originated from Mexico, and others like *A. blitum*, *A. thunbergii*, *A. sparganiocephallus*, *and A. graecizans*, are indigenous to Africa (Maundu et al., 1999). At least 17 species have edible leaves and three are grain amaranth. There are also those that are multipurpose and are used for grain and vegetable productions such as *Amaranthus cruentus.* Amaranth leaves and seeds are rich sources of protein, iron, calcium, zinc, and vitamins A, C, E tocotrienol, a rare and beneficial form of vitamin E and squalene, and essential amino acids including lysine (Van der walt et al., 2009).

However, amaranths throughout the world are damaged by several insect species (Wilson, 2014); Kagali et al., 2013; Louw, S, 1995). These pests have become a major limiting factor in the production of these vegetables worldwide. In South Africa, seven weevil species; *Hypolixus haerens* (Coleoptera: Curculionidae), *Gasteroclisus* cf *cuneiformis* (Coleoptera: Curculionidae), *Neocleonus sannio* (Coleoptera: Curculionidae), *Baris* cf *dodonis* (Coleoptera: Curculionidae), *Baris* cf *amaranth* (Coleoptera: Curculionidae), and *Hypurus* sp. (Coleoptera: Curculionidae) were found to infest both wild and cultivated vegetable *Amaranthus* spp. (Louw, S, 1995). At Ibadan in Nigeria, leaf defoliating pests were reported (Aderolu et al., 2013). In Meru County of Kenya, C*letus sp.* (Heteroptera: Coreidae), *Hepertogramma bipunctalis* (Lepidoptera: pyralidae), *Hypolixus nubilosus* (Coleoptera: Curculionidae), and grasshoppers were also among the pests reported to infest amaranth (Kagali et al., 2013).

1.3 African nightshades and associated pests

The African nightshade, *Solanum scabrum* is a green leafy vegetable rich in vitamins proteins, minerals, and contains phenols and alkaloids such as nicotine, quinine, cocaine, and morphine known for their medical properties (Ochieng et al., 2007). However, African nightshades suffer damage caused by several arthropod pests including spider mites, black aphids (*Aphis fabae*), leaf miners *(Lyriomyza* spp), leaf hoppers, Flea beetles (Chrysomelidae spp), Root-knots nematodes (*Meloidyne* spp), African bollworm (*Helicoverpa armigera*), weevils (*Systates pollinosus*), and cutworms (*Agrotis* spp) (Kipkosgei 2004; Weller et al, 2013; Mureithi et al., 2017).

1.4 Ethiopian kale and associated pests

The Ethiopian kale, *Brassica carinata* also referred to as African kale is a plant originating from the Ethiopian Plateau (Grubben et al., 2004). The plant is used as a leafy vegetable in Africa (Adeniji & Aloyce, 2014) as well as an oilseed crop in Asia (Kular & Kumar, 2011), USA, and Europe (Seepaul et al., 2016). Ethiopian kale leaves, tender stems, and flowers are all used as vegetables which have high nutritional value with higher protein content compared to Spinach (Fordham & Hadley, 2003), Vitamin C, Calcium, Iron, and Zinc higher than *Brassica juncea* (Shackleton et al., 2009). Ethiopian kale also contains cancer preventing compounds (Odongo et al., 2017). Seeds yield more than 40% oil although it is not edible due to high levels of undesirable erucic acid and glucosinolates but is suitable for industrial uses such as biodiesel and chemical additives in plastic, tannery, and cosmetics (Bozzini et al. 2007). However, new cultivars containing low levels of erucic acid have been developed for the production of edible oil (Velasco *et.al*, 2004). Among the major insect pests of Ethiopian kales are cabbage butterfly (*Pieris brassicae* (Lepidoptera: Pieridae), mustard sawfly (*Athalia proxima* (Hymenoptera: Tenthredinidae)), flea beetles (*Phyllotreta spp*. (Coleoptera: Chrysomelidae)), Hurricane bug (*Bagrada hilaris* (Hemiptera: Pentatomidae)), cabbage aphid (*Brevicoryne brassicae* (Hemiptera: Aphididae)), green peach aphid (*Myzus persicae*

(Hemiptera: Aphididae)), cabbage whiteflies (*Aleyrodes proletella* (Hemiptera: Aleyrodidae)(Kumar, 2017; Reddy, 2017).

1.5 Plant nutrition in pest management

The use of plant resistance is considered a major control strategy for herbivorous pests. Host plant resistance to pest is characterized as antixenosis, antibiosis and tolerance. In antixenosis feeding and oviposition are discouraged, antibiosis interferes with sustained pests infestation i.e. breeding, development, and survival, while tolerance is the ability of the plant to compensate for pest damage (Wiseman, 1985). Although host plant resistance traits are primarily inherent, the application of water and fertilizers to plants causes physiological morphological, and biochemical changes in plants affecting resistance or susceptibility to pests (Ashilenje et al, 2012; Louda & Collinge, 1992). Application of fertilizer and water to crops provides supplemental nutrition resulting in desirable effects such as improved crop growth and yield potential (Kipkosgei et al, 2003). However, it is important to recognize that the focus of fertilizer use as a means to increase yields can lead to excess or unbalanced fertilization causing undesirable effects such as susceptibility of the crop to pests (Rashid et al., 2017). For example, in rice, several studies have shown nutrient imbalances caused by rates of fertilizer application impact both crop growth and pest outbreaks. On one hand, higher rates of nitrogen causing high plant growth but also higher outbreaks of brown leafhoppers, stem borer, and leaf folder (Chau et al., 2003). Plant tissue nutrients affect the quality of host plants to herbivores and therefore may influence plant susceptibility to pest (Geddes, 2010). In this respect, there is a relationship between pest management methods used by farmers and soil fertility management strategies (Altieri & Nicholls, 2003; Zehnder et al., 2007). Therefore, considering the potential of AIVs in improving the nutrition and livelihood of venerable communities on one hand and the large yield losses caused by herbivorous pests on the other hand, more effective and affordable pest control measures are required. Among the possible strategies for pest control in AIVs is the management of irrigation and fertilization regimes.

1.6 Research objective

Although pest status of herbivorous arthropods is dynamic and changes with season, year, country, plant species, variety, cultivar, and cropping systems, extensive studies have not been carried out to identify pest species and determine the level of damage they cause in amaranth, African nightshades and Ethiopian kales in Tanzania to focus pest management resources based on the relative importance of each pest. Besides, naturally occurring natural enemies of pests that could be used for pest control in these crops have not been widely explored. Also, despite the influence of plant nutrition in susceptibility of plants to herbivores, effects of application rates of water and fertilizers on pests of African nightshade have not been studied.

The study aimed to answer the following questions;

1. What are abundance, diversity and damage levels of arthropod pests in amaranth, African nightshades and Ethiopian kale in Tanzania and their natural enemies?
2. How does fertilizer and water regimes the influence host selection of *Tetranychus evansi* on *Solanum scabrum*?
3. How does fertilizer and water regimes affect the population of *Tetranychus evansi*, its leaf damage and leaf alkaloid content in *Solanum scabrum*?

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2 Distribution and diversity of insect pests of leaf amaranth and their associated natural enemies in Tanzania

2.1 Abstract

Amaranth is the most traded African leafy vegetable in Tanzania. However, arthropod pests remain a great challenge in its production. Despite high losses caused by pest damage, there is little information on the identity of major insect species damaging amaranth in Tanzania. In 2014 eight amaranth growing areas of Tanzania were surveyed in the wet and dry seasons. Distribution and diversity of insect pests and their associated natural enemies were identified. Diversity in terms of species richness was higher in the low altitude zones during the dry and wet seasons of 2014. Lepidopteran species were the main pests of amaranth causing 12.8% damage in the dry season and 10.8% in the wet season. Other pest orders were hemipterans (9.5% and 8.5%), coleopterans (6.5% and 7.9%), orthopterans (5.5% and 2.2%), Acari (1.5% and 3%) and dipterans (1.1% and 0.8%) in the dry and wet seasons respectively. Hymenopteran species, mainly aphid parasitoid *Aphidius colemani*, were the most abundant natural enemy species. Other abundant natural enemies were coccinellid beetles (Coleoptera), aphidophagous gall midges and hoverfly larvae (Diptera). Information from this study will create awareness to farmers on major pests infesting amaranth for better and timely pest control. The diverse natural enemy species observed in the fields can be further exploited to manage pest populations in economically important crops.

Key words: Vegetables, feeding guild, seasonal abundance, beneficial insects, crop protection

2.2 Introduction

Amaranth is an important African indigenous vegetable (AIV) in Tanzania that plays a key role in improving nutrition and income among smallholder growers. It is the most traded African leafy vegetable in Tanzania with more than 80% of vegetable traders stocking the vegetable (Lotter, 2014). According to a report on the national sample census of agriculture in Tanzania (NBS, 2012) more than 17,000 households were involved in the production of amaranth. The leafy vegetable accounted for 3% of the total fruits and vegetables produced in the country with Dar es Salaam region being the highest producer of amaranth.

The genus amaranth has more than 100 species out of which 17 have edible leaves and 3 are grain amaranth. Amaranth leaves are rich sources of protein, iron, calcium, zinc, and vitamins A, C, and E (Assad et al., 2017). Amaranth seeds are rich in essential amino acids including lysine (Van der walt et al., 2009) and have 15% gluten-free protein content with the digestibility of up to 90%. Additionally, amaranth seeds contain 5-9% high-quality oil with tocotrienols, a form of vitamin E and squalene; a compound known for its anti-cancer properties (Amicarelli & Camaggio, 2012).

Production of amaranth vegetable in Tanzania is throughout the year; during the two rainy seasons and under irrigation during the dry season from June to September. The two rainy seasons are the long rainy season also known as *Masika* that occurs between March to May and the second is the short rainy season also known as *Vuli* that occurs between October to December (Keller, 2004). However, a study carried out in four districts of Tanzania reported that 36-42% of villages regarded pests and diseases as major production constraints of African indigenous vegetables in all seasons (Keller, 2004).

2.3 Insect pests of amaranth

Amaranths are damaged by a number of insect species (Mureithi et al. 2017). In South Africa, *Hypolixus haerens*, *Gasteroclisus* cf *cuneiformis*, *Neocleonus sannio*, *Baris* cf dodonis, Baris cf amaranth, Baris sp. and *Hypurus* sp. were seven weevil species found to infest both wild and cultivated vegetable *Amaranthus* spp. (Louw, 1995). At Ibadan in Nigeria, 31 species collected were defoliators while 12 species were predators (Aderolu, 2013). In Meru county of Kenya, Kagali et al. (2013) reported Coreid bugs, *Cletus* sp. webworms, *Hepertogramma bipunctalis*, Amaranth weevil, *Hypolixus nubilosus* and grasshoppers as the major leaf and stem damaging pests. However, a study on the production and consumption of AIVs in Tanzania reported aphids as major pests during the rainy and cold seasons in Arumeru district while in Singida district defoliators, stem borers and grasshoppers were important pests during the dry season although specific species were not reported (Keller, 2004).

Pest control in amaranth just like other vegetables grown in Tanzania is mainly through the use of synthetic chemical pesticides despite their adverse effects on humans and environmental health. A study carried out in Northern Tanzania indicated that more than 50% of vegetable farmers reported an increasing trend in their use of pesticides in the control of pests and diseases. Consequently, a study on the pesticide residues in table-ready food in Tanzania observed that 72% of amaranth samples tested exceeded the method detection limits (Ndengerio-Ndossi & Cram, 2005) highlighting pesticide residues as a growing health concern among consumers. However, despite the concerns on the use of pesticides, pests develop resistance and continue to cause considerable yield losses in vegetable production.

Given current pest management challenges, loss in yields and inadequate information on pest identification, a survey was carried out in different altitudes and seasons in Tanzania during 2014 to identify the species diversity, seasonal and altitudinal distribution, damage and associated natural enemies of insect pests of amaranth. As a result, the findings will serve as the first step in developing effective integrated pest management strategies.

2.4 Methodology

2.4.1 Survey Area

A field survey was carried out in eight selected amaranth growing regions of in Tanzania to identify arthropod pests and natural enemies in amaranth (Figure 2-1). These regions were Arusha, Dodoma, Kilimanjaro and Mbeya in the mid altitudes (1000-1800 masl) while Dar es Salaam, Pwani, Morogoro, and Tanga were areas in low altitude (0-1000 masl). In each region, there were two districts, three farms per district and one crop field at the harvesting stage per farm. The districts were Arusha and Meru districts in Arusha region, Muheza and Lushoto in Tanga, Hai and Moshi in Kilimanjaro, Mbeya Municipal and Mbozi in Mbeya, Kongwa and Mpwapwa in Dodoma, Morogoro and Kilosa in Morogoro, Kibaha and Bagamoyo in Pwani, Ilala and Kinondoni in Dar es Salaam. The survey was carried out during the dry season (June-July) and wet season (October-November) of 2014.

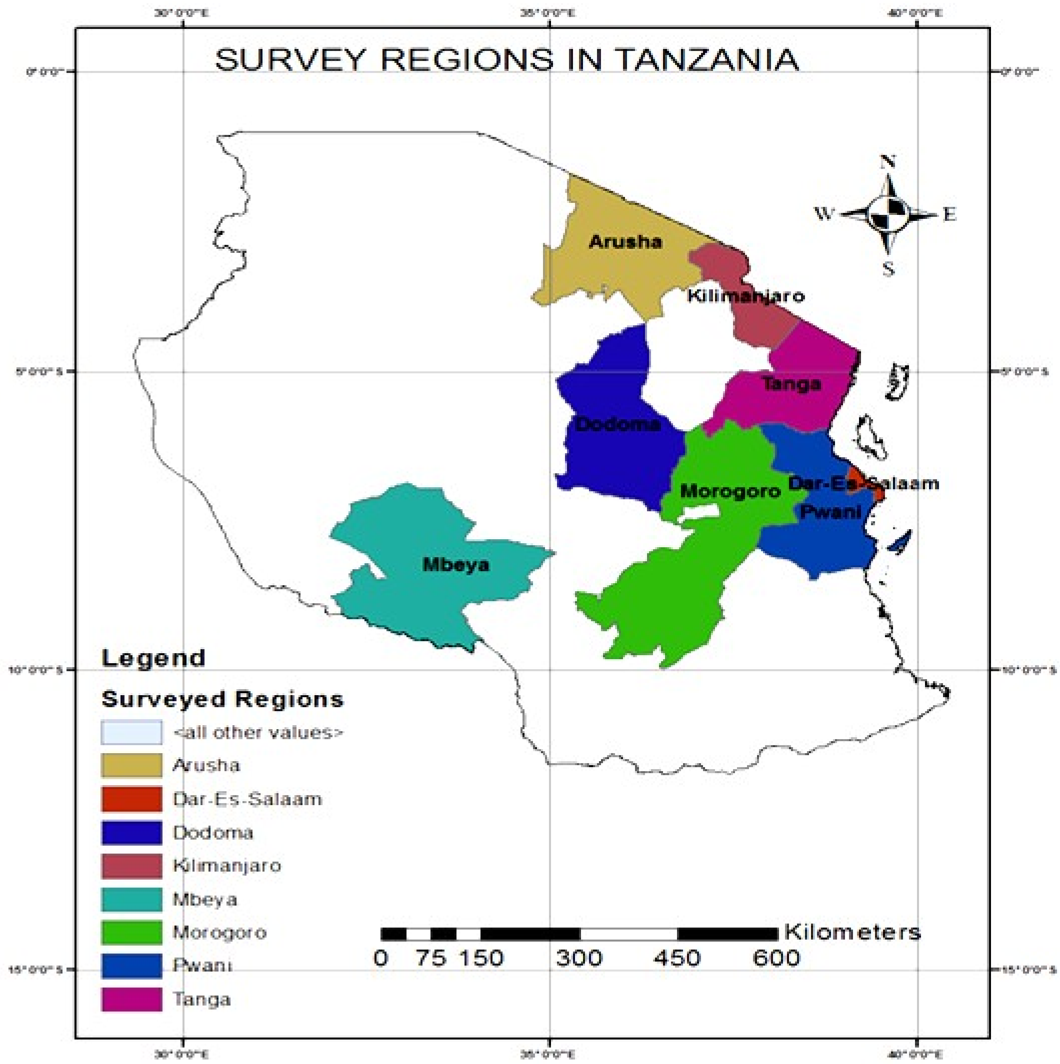

Figure 2-1: A map showing the eight regions surveyed in Tanzania

2.4.2 Sampling

Samples of insects were obtained from each amaranth field by dividing an area not exceeding a quarter-acre into four quadrants and ten plants were randomly selected from each quadrant and observed for the presence of pests and damage levels. The samples were collected by the use of 30 cm diameter sweep nets to capture flying insects and then drowned in 70% ethanol. The tapping of the plant 10-15 times was used to dislodge insects from a plant to a trapping tray; 32 x 23.5 cm, sprayed with 70% ethanol to immobilize them. Hand-picking of large docile insects and plant material infested with immature stages of insects was also used.

Live insect samples such as eggs, larval, pupa, and adults collected on plant material from the field, were placed into plastic boxes lined with a paper towel to absorb excess moisture and covered with a netting ventilated lid to facilitate transportation to the ICIPE laboratory where they were stored before and after identification. In the laboratory, larval stages were fed with fresh plant material daily to allow for successful development while the pupae and mummies of parasitized insects were provided with suitable conditions to ensure adult emergence. Dead insect samples were preserved with 70% ethanol in plastic vials (25 mm in diameter, 90 mm in depth). Adult insect samples were sorted into orders, mounted on insect cards using insect pins or glass slides, and identified using the morphological keys by entomologists at Tengeru Horticultural Research and Training Institute in Arusha, Tanzania, International Centre of Insect Physiology and Ecology (ICIPE) in Nairobi, Kenya and confirmed at National Museums of Kenya.

2.4.3 Species diversity

Species diversity in different altitudes of dry and wet seasons was analyzed using the BiodiversityR package in R version 3.4.1 (R Core Team, 2017). The results were generated as Renyi diversity profiles that summarize several diversity indices. Species richness is the total number of species and gives equal weight to dominant and rare species. Species evenness shows the degree to which the total individuals are divided among species, where low values show only one or a few species dominate and high values point to relatively the same number of individuals in each species. Shannon index (Shannon, 1948) represents the uncertainty for the identity of an unknown individual with high uncertainty depicting high diversity while ease of predicting its identity denotes low diversity. Simpson index is the probability that two randomly chosen individuals are of the same species (Simpson, 1949) with low probability meaning high diversity. To achieve this, species relative abundance was obtained by dividing the observed abundance by the total abundance. In this case, the observed abundance was the total number of individuals counted in each species while the total abundance was the total sum of arthropods counted during the survey.

2.4.4 Damage assessment

Damage levels were determined using the scores in Table 2-1. The percentage damage range at each damage score was used to calculate a percentage midpoint that was angular transformed before Analysis of variance was performed with R version 3.4.1 (R Core Team, 2017). The analysis was done separately for the dry and wet season.

Table 2-1: Pest damage scores used for assessing damage levels for various pests

Insect	Damage score	Description of damage	Reference
Aphids	0	Plant appears healthy	Webster et al. 1987
	1	1-25 % chlorosis and leaf folding	
	2	26-50 % chlorosis and leaf folding	
	3	51-75 % chlorosis and leaf folding	
	4	75-100% chlorosis and leaf folding	
Coleopterans	0	No visible damage	(Smith, 2000) modified
	1	1-20% 1-10 holes	
	2	21-40% 10-20 holes	
	3	41-60% 20-30 holes	
	4	61-80% above 30 holes	
	5	81-100% leaf drying	
Lepidopterans	0	No leaf damage	(Said & Itulya, 2003) modified
	1	1-25 % of leaf consumed	
	2	26-50 % of leaf consumed	
	3	51-75 % of leaf consumed	
	4	76-100 % of leaf consumed	
Thrips	1	No leaf damage	(Michelotto et al., 2013) modified
	2	1-25% few silvery streaking	
	3	26-50% moderate streaking	
	4	51-75% heavy streaking and curling	
	5	75-100% silvery and shriveling	
Grasshoppers	1	1-20% foliage consumed	(Capinera, 1993) modified
	2	21-40% foliage consumed	
	3	41-60% foliage consumed	
	4	61-80% foliage consumed	
	5	81-100% foliage consumed	
Leaf miners	1	No damage	(CIP, 2006)
	2	1-25% foliage damage	
	3	26-50% foliage damage	
	4	51-75% foliage damage	
	5	75-100% foliage damage	
Mites	0	No damage	(Hussey & Parr, 1963) modified
	1	1-20% leaf damage	
	2	21-40% leaf damage	
	3	41-60% leaf damage	
	4	61-80% leaf damage	
	5	81-100% leaf damage	

2.5 Results

2.5.1 Abundance of insect pests in amaranth

A total of 7705 arthropods were identified in this study which included 7127 pests and 581natural enemies. The dry season had 4059 pests and 231 natural enemies while there were 3065 pests and 345 natural enemies in the wet season. There were 22 species in Coleopteran, 20 in Hemiptera, 12 in Lepidoptera, 9 in Orthoptera, 4 in Thysanoptera, and 1 in Diptera order (Table 2-2).

Table 2-2: Composition and abundance of pest species observed in amaranth fields during the 2014 survey in Tanzania. Means indicate the insects per plant per farm, n=99.

Order	Family	Species	Mean±SE Dry season	Mean±SE Wet season
Hemiptera	Aphididae	*Aphis fabae*	0.634±0.264	0.356±0.168
Hemiptera	Aphididae	*Myzus persicae*	0.260±0.112	0.120±0.046
Hemiptera	Aphididae	*Aphis craccivora*	0.146±0.122	0.163±0.075
Hemiptera	Aleyrodidae	*Bemisia tabaci*	0.059±0.026	0.006±0.006
Hemiptera	Coreidae	*Cletus indicator*	0.016±0.005	0.011±0.004
Lepidoptera	Crambidae	*Spoladea recurvalis*	0.012±0.004	0.007±0.003
Lepidoptera	Noctuidae	*Helicorvepa armigera*	0.012±0.004	0.000±0.000
Hemiptera	Pentatomidae	*Nezara viridula*	0.012±0.002	0.006±0.002
Lepidoptera	Crambidae	*Udea ferrugalis*	0.010±0.004	0.002±0.002
Coleoptera	Curculionidae	*Lixus rhomboidalis*	0.010±0.003	0.013±0.004
Coleoptera	Curculionidae	*Baris* sp.	0.010±0.002	0.012±0.003
Coleoptera	Curculionidae	*Hypolixus pulvisculosus*	0.008±0.006	0.000±0.000
Orthoptera	Pyrgomorphidae	*Zonocerus elegans*	0.007±0.004	0.002±0.002
Coleoptera	Curculionidae	*Hypolixus truncatulus*	0.007±0.002	0.007±0.003
Lepidoptera	Crambidae	*Hepertogramma bipunctalis*	0.005±0.003	0.003±0.002
Orthoptera	Gryllidae	*Teleogryllus* sp.	0.005±0.002	0.000±0.000
Hemiptera	Lygaeidae	*Nysius* sp.	0.004±0.002	0.006±0.004
Orthoptera	Pyrgomorphidae	*Phymateus viridipes*	0.004±0.002	0.003±0.002
Thysanoptera	Thripidae	*Haplothrips gowdeyi*	0.003±0.034	0.004±0.003
Hemiptera	Pyrrhocoridae	*Dysdercus albofasciatus*	0.003±0.003	0.000±0.000
Hemiptera	Pentatomidae	*Bagrada hilaris*	0.003±0.002	0.002±0.002
Hemiptera	Pentatomidae	*Agonoscelis versicolor*	0.003±0.002	0.000±0.000
Lepidoptera	Crambidae	*Psara atritermina*	0.003±0.001	0.001±0.001
Coleoptera	Chrysomelidae	*Bruchus* sp.	0.002±0.002	0.000±0.000
Coleoptera	Curculionidae	*Systates crenatipennis*	0.002±0.002	0.000±0.000

Order	Family	Species	Mean±SE Dry season	Mean±SE Wet season
Hemiptera	Coreidae	*Cletus orientalis*	0.002±0.002	0.028±0.002
Lepidoptera	Noctuidae	*Sesamia* sp.	0.002±0.002	0.000±0.000
Coleoptera	Apionidae	*Apion* sp.	0.002±0.001	0.002±0.001
Coleoptera	Chrysomelidae	*Aulocophora foveilcollis*	0.002±0.001	0.001±0.001
Coleoptera	Tenebrionidae	*Lagria villosa*	0.002±0.001	0.001±0.006
Coleoptera	Chrysomelidae	*Phyllotreta* sp.	0.002±0.001	0.000±0.000
Diptera	Agromyzidae	*Lyliomyza* sp.	0.002±0.001	0.002±0.001
Hemiptera	Cercopidae	*Locris areata*	0.002±0.001	0.001±0.001
Hemiptera	Lygaeidae	*Graptostethus electus*	0.002±0.001	0.005±0.002
Lepidoptera	Noctuidae	*Spodoptera litorralis*	0.002±0.001	0.006±0.004
Orthoptera	Pyrgomorphidae	*Atractomorpha* sp.	0.002±0.001	0.000±0.000
Orthoptera	Pyrgomorphidae	*Pyrgomorphella albini*	0.002±0.001	0.000±0.000
Coleoptera	Curculionidae	*Nematocerus* sp.	0.002±0.000	0.003±0.004
Coleoptera	Bruchidae	*Acanthoscelides maculatus*	0.001±0.001	0.001±0.001
Coleoptera	Curculionidae	*Anametis* sp.	0.001±0.001	0.001±0.001
Coleoptera	Curculionidae	*Babaultia* sp.	0.001±0.001	0.001±0.001
Coleoptera	Meloidae	*Epicauta albovittata*	0.001±0.001	0.000±0.000
Coleoptera	Chrysomelidae	*Epitrix siluicola*	0.001±0.001	0.000±0.000
Coleoptera	Chrysomelidae	*Hapsidolema nigroparallela*	0.001±0.001	0.000±0.000
Coleoptera	Tenebrionidae	*Lagria cuprina*	0.001±0.001	0.000±0.000
Coleoptera	Coccinellidae	*Lema conradi*	0.001±0.001	0.000±0.000
Hemiptera	Coreidae	*Acanthocoris fasciata*	0.001±0.001	0.000±0.000
Hemiptera	Lygaeidae	*Nysius binotatus*	0.001±0.001	0.005±0.004
Hemiptera	Pentatomidae	*Halyomorpha* sp.	0.001±0.001	0.000±0.000
Hemiptera	Pentatomidae	*Antestia* sp.	0.001±0.001	0.000±0.000
Lepidoptera	Noctuidae	*Spodoptera exigua*	0.001±0.001	0.002±0.001
Lepidoptera	Zygaenidae	*Syringura* sp.	0.001±0.001	0.000±0.000
Orthoptera	Acrididae	*Dichromorpha* sp.	0.001±0.001	0.000±0.000
Orthoptera	Acrididae	*Schistocerca gregaria*	0.001±0.001	0.001±0.001
Orthoptera	Zonocerus sp.	*Zonocerus* sp.	0.001±0.001	0.000±0.000
Thysanoptera	Thripidae	*Megalurothrips sjostedti*	0.001±0.001	0.008±0.005
Coleoptera	Formicidae	*Haltica* sp.	0.000±0.000	0.001±0.001
Coleoptera	Tenebrionidae	*Lagria cyannicollis*	0.000±0.000	0.000±0.000
Coleoptera	Coccinellidae	*Lema ornatula*	0.000±0.000	0.001±0.001
Hemiptera	Alydidae	*Laptocoris* sp.	0.000±0.000	0.001±0.001
Hemiptera	Pentatomidae	*Asparia armigera*	0.000±0.000	0.001±0.001
Hemiptera	Pyrrhocoridae	*Dysdercus fasciata*	0.000±0.000	0.002±0.002
Lepidoptera	Crambidae	*Psara bipunctalis*	0.000±0.000	0.002±0.001
Lepidoptera	Gelechiidae	*Tuta absoluta*	0.000±0.000	0.000±0.000
Lepidoptera	Plutellidae	*Plutella xylostella*	0.000±0.000	0.002±0.002

2.5.2 Abundance of Lepidoptera pest species in amaranth

There was a significant difference ($F_{(11, 198)}$ = 4.62, p<0.001) in abundance between the twelve Lepidopteran species observed on amaranth fields during the 2014 survey. The most abundant species was *Spoladea recurvalis* with a mean of 0.009±0.02 insects per plant and accounted for 30.3% of the total Lepidopterans collected during the survey. The other major species were *Udea ferrugalis*, *Spodoptera littoralis,* and *Hepertogramma bipunctalis* (Table 2-2). However, there were no differences between seasons ($F_{(1, 1140)}$ =1.36, p=0.24) or altitudes ($F_{(1, 1140)}$ = 0.5, p=0.47). The abundance and distribution of the three most abundant lepidopteran species i.e. *S. recurvalis, U. ferrugalis,* and *S. littoralis* are shown in Figure 2-2.

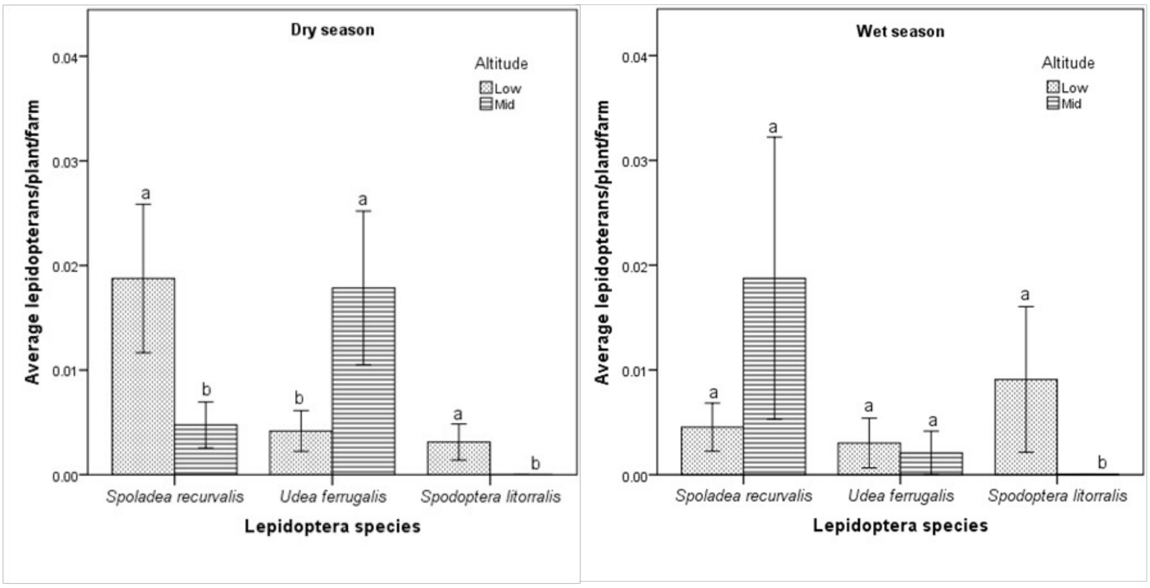

Figure 2-2. Mean of *S. recurvalis*, *U. ferrugalis* and *S. litorralis* per plant per amaranth farm at low and mid-altitude zones during the dry season (left graph) and wet season (right graph) of the 2014 survey carried out in eight regions of Tanzania. (ANOVA; Means compared using Tukey test, p=0.05, n=99).

2.5.3 Abundance of Hemiptera pest species in amaranth

There were eleven families in the Hemiptera order with Aphididae being the most abundant accounting for 79.3% of insects in the order. Others were Aleyrodidae (4.7%), Coreidae (2.5%), Pentatomidae (2.2%), Lygaeidae (1.6%), Pyrrhocoridae (0.4%), Miridae (0.35%), Cercopidae (0.2%), and Alydidae (0.1%). There was no difference in abundance between the three aphid species (F (2, 285) = 4.05, p=0.18). *Aphis fabae* with a mean of 0.48±0.14 aphids per plant was the most abundant aphid accounting for 59% of the all the aphids counted while *Myzus persicae* (0.18±0.06) accounted for 22% and *Aphis craccivora* (0.16±0.07) accounting for 19% of the total aphids collected during the survey. However, there were no significant differences in abundance of aphids between seasons ($F_{(1, 285)} = 0.60$, p=0.44) or between altitudes ($F_{(1, 285)} = 0.83$, p=0.36) (Figure 2-3).

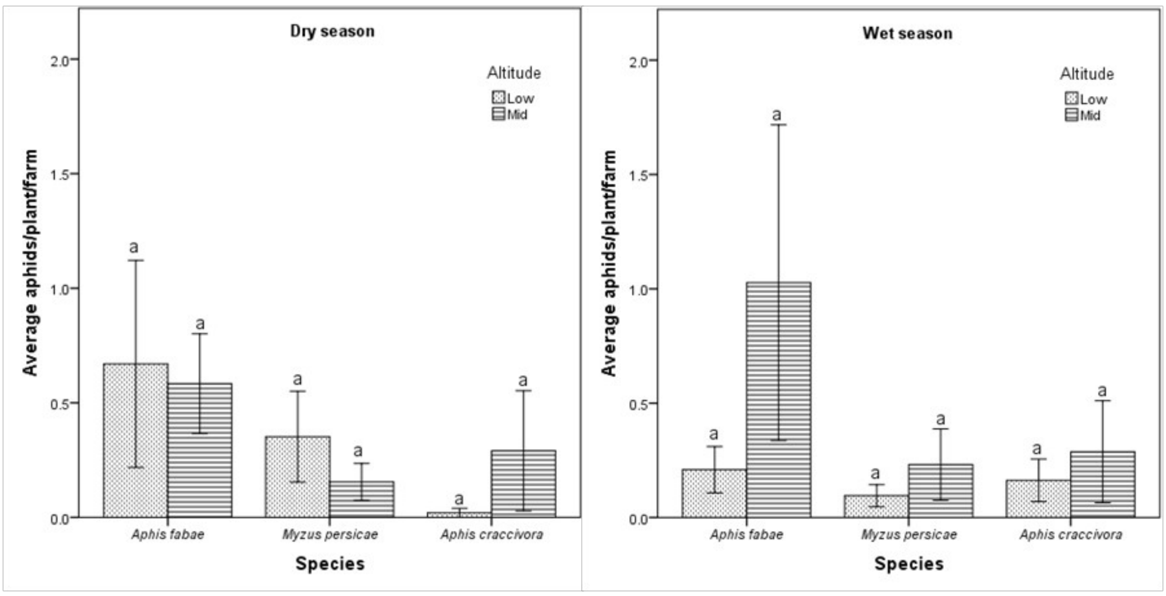

Figure 2-3: Mean number of *A. fabae*, *M. persicae* and *A. crassivora* per plant per farm in the low and mid-altitude zones in eight regions of Tanzania during the dry (left graph) and wet season (right graph) in 2014. ANOVA; Means compared using Tukey test, p=0.05, n=99)

2.5.4 Abundance of Coleoptera pest species of amaranth

There was a significant interaction between season and species ($F_{(21,\ 1892)} = 1.15$, p=0.02) in the abundance of the Coleopteran species observed on amaranth fields during the 2014 survey. The wet season had a higher abundance of beetles per plant (0.003±0.0004) than the dry season (0.002±0.0003) each accounting for 58% and 42% of the total coleopterans respectively. The distribution of the three most abundant species; *Baris sp*. (22.2%), *Lixus rhomboidalis* (20.5%) and *Hypolixus trunctalus* (14.6%) in the dry and wet seasons across low and mid-altitude areas is shown in Figure 2-4.

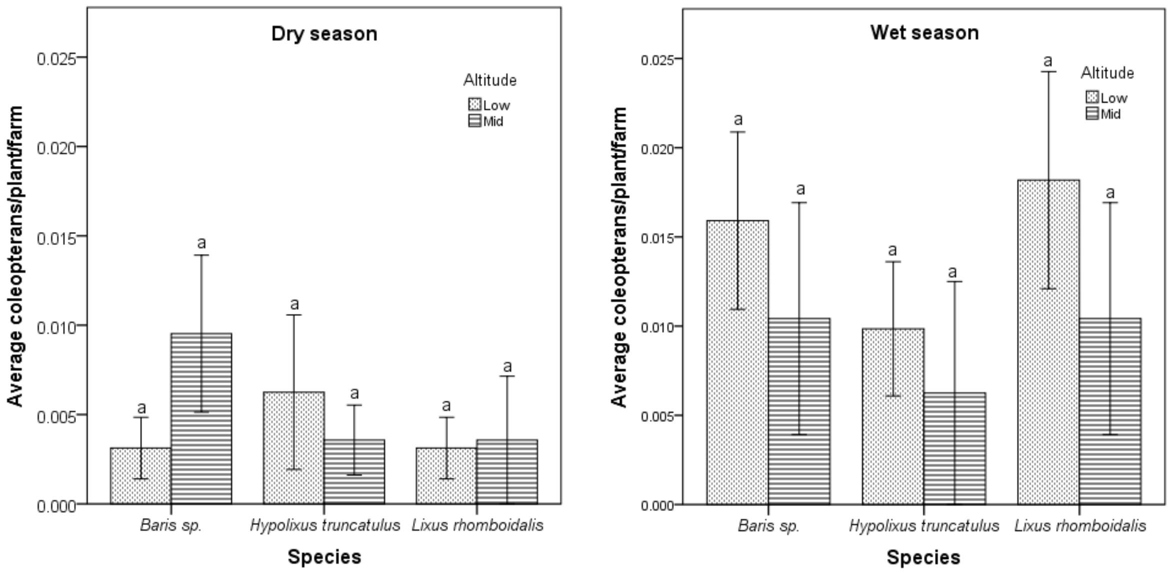

Figure 2-4: Mean number of *Baris sp.*, *H. truncatulus*, *L. rhombaidalis* per plant per amaranth farm in the low and mid-altitude zones during dry season (left graph) and wet season (right graph) of the 2014 survey carried out in eight regions of Tanzania. (ANOVA; Means compared using Tukey test, p=0.05, n=99).

2.5.5 Abundance of Orthopteran pest species of amaranth

There was a difference in Orthopteran abundance between seasons ($F_{(1, 688)}$ = 4.83, p=0.03) with more grasshoppers in the dry season (79%) than in the wet season (21%). However there were no significant differences between altitude ($F_{(1, 688)}$) = 0.74, p=0.48) or between species ($F_{(1, 688)}$ = 0.18, p=0.99). The most abundant species were *Zonocerus elegans* (35.4%), *Phymateus viridipes* (25.0%) and *Teleopgryllus sp.* (18.8%). When the abundance of each of the three species was compared between low and mid altitudes, there was no difference in *Zonocerus elegans* (t=0.92, df=43, p=0.365), *Phymateus viridipes* (t=0.12, df=43, p=0.904) or *Teleogryllus sp*. (t=1.05, df=43, p=0.303) in the dry season. Similarly, there were no significant differences for *Zonocerus elegans* (t=0.598, df=43, p=0.559), *Phymateus viridipes* and (t=0.30, df=43, p=0.766) between low and mid-altitude in wet season (Figure 2-5). However, *Teleopgryllus sp*. was not observed during the wet season.

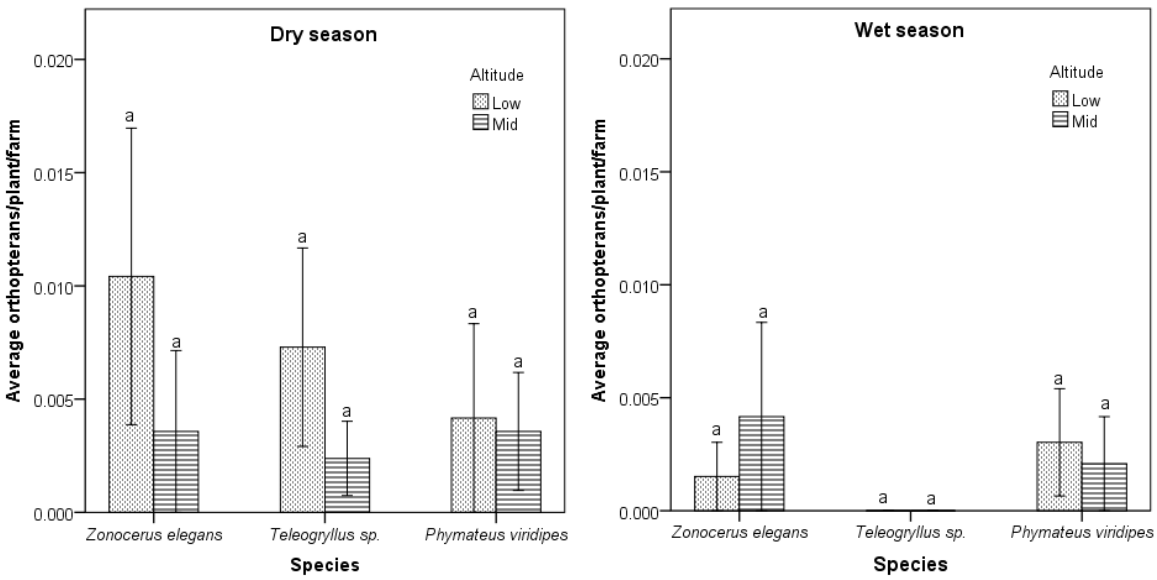

Figure 2-5: Mean number of *Z. elegans*, *Teleogryllus sp.* and *P. viridipes* per plant per amaranth farm in the low and mid-altitude zones during dry season (left graph) and wet season (right graph) of the 2014 survey carried out in eight regions of Tanzania. (ANOVA; Means compared using Tukey test, p=0.05, n=99).

There was a difference in thrips abundance between seasons ($F_{(1, 380)} = 5.93$, p=0.02) with means of 0.0003±0.0002 and 0.004±0.002 thrips per plant for dry and wet season respectively. The abundance of the stalk-eyed fly, *Diopsis servillei* was significantly higher (t=2.98, df=88, p=0.004) in the mid (0.125±0.0067) than in the low (0.00038±0.0004) altitude zones in the wet season, while in the dry season there was no significant difference (t=1.22, df=88, p=0.23) between low and mid-altitude regions.

2.5.6 Abundance of arthropod natural enemies observed in amaranth

A variety of natural enemies belonging to 5 orders and 9 families were observed in amaranth fields (Table 2-3). These included aphid parasitoids in Hymenoptera, Coccinellids (Coleoptera), rove beetles (Coleoptera), dipterans aphid midge, and hoverfly, damselfly (Odonata), and green lacewing (Neuroptera).

Table 2-3: Natural enemy species encountered in amaranth fields during the 2014 survey conducted across eight regions of Tanzania. The mean and SE are based on 40 plants per farm (n=99).

Order	Family	Species	Prey	Mean±SE
Hymenoptera	Braconidae	*Aphidius colemani*	Aphids	1.15±0.450
Coleoptera	Coccinellidae	*Scymnus trepidulus*	Aphids, spiders	0.40±0.233
Coleoptera	Coccinellidae	*Cheilomenes sulphurea*	Aphids	0.21±0.075
Neuroptera	Chrysopidae	*Chrysoperla carnea*	Aphids	0.20±0.068
Hymenoptera	Braconidae	*Apanteles* sp.	Leaf webbers	0.18±0.082
Coleoptera	Coccinellidae	*Scymnus levaillanti*	Aphids	0.14±0.085
Diptera	Syrphidae	*Syrphid sp.*	Sucking insects	0.14±0.059
Coleoptera	Coccinellidae	*Hippodamia variegate*	Aphids	0.13±0.082
Coleoptera	Coccinellidae	*Cheilomenes aurora*	Aphids	0.07±0.034
Odonata	Coenagrionidae	*Africallagma elongatum*	Aphids, spiders	0.05±0.039
Coleoptera	Coccinellidae	*Exochomus nigrimaculatus*	Aphids	0.05±0.032
Coleoptera	Staphylinidae	*Paederus* sp.	Insects	0.04±0.026
Diptera	Cecidomyiidae	*Aphidoletes aphidimyza*	Aphids	0.04±0.026
Coleoptera	Coccinellidae	*Brumoides fulviventris*	Aphids	0.03±0.024
Coleoptera	Coccinellidae	*Harmonia* sp.	Aphids	0.02±0.015
Hemiptera	Pentatomidae	*Asopinae* sp.	Insects	0.01±0.011
Odonata	Coenagrionidae	*Africallagma subtile*	Aphids, spiders	0.01±0.011

2.5.7 Species diversity of amaranth pests

The Renyi diversity profile of the mid-altitude regions was above that of the low altitude zones in the dry season indicating that there was higher species diversity in mid than low altitude zones (Figure 2-6). Species richness indicated by H-alpha value at alpha=0 was higher in the mid (4.15) than in the low (3.5) altitude. Species evenness, Shannon, and Simpson values were lower in the low that mid-altitude zones indicating that a few species accounted for a large part of the total arthropods collected. The Renyi diversity profiles of low and mid-altitude zones of the wet season touched each other indicating that there was no difference in species diversity (Figure 2-6).

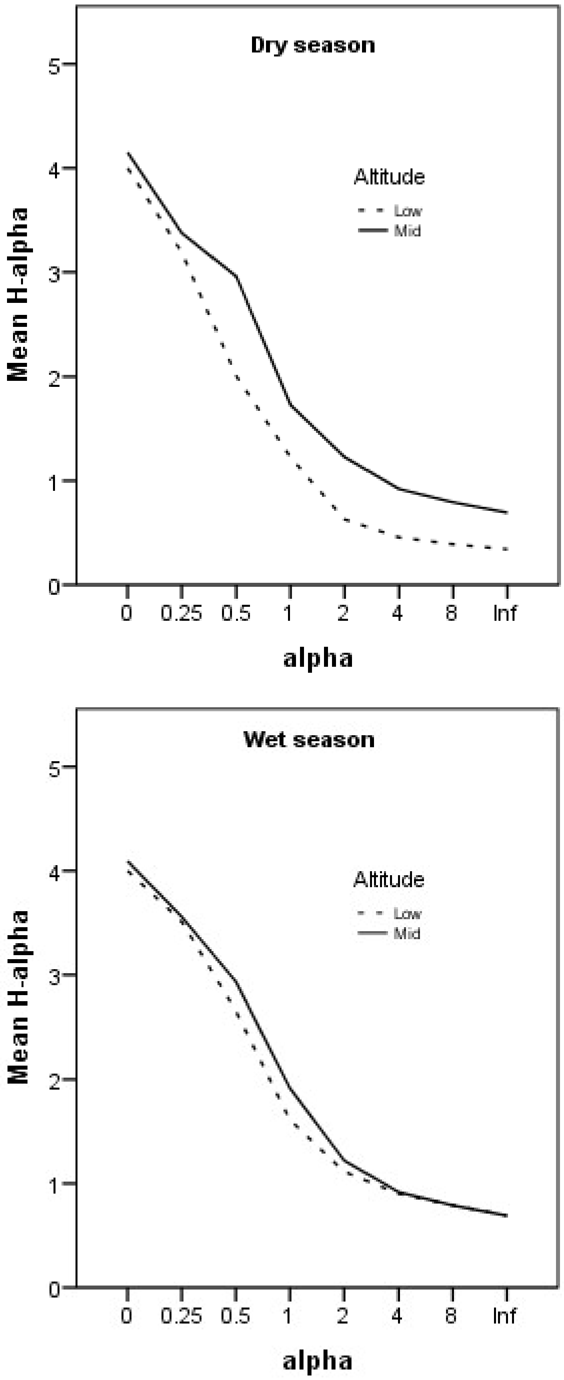

Figure 2-6: Renyi diversity profiles for amaranth pests and associated natural enemies in low and mid altitude zones during the dry season (left graph) and wet season (right graph) of 2014 survey carried out in eight regions of Tanzania.

2.5.8 Damage levels associated with arthropod pests of amaranth

There was a significant difference ($F_{(6, 273)}$ =18.23, p<0.001) in damage caused by feeding guilds, i.e. pest orders, in the dry season. Lepidopterans caused the highest damage of 12.8% followed by Hemiptera (9.5%), Coleoptera (6.5%), Orthoptera (5.3%), Acari (1.4%) and Diptera caused the least damage of 1.1%. In the wet season, there was a significant difference ($F_{(6, 273)}$ =8.317, p<0.001) in the damage caused by feeding guilds. Lepidopterans caused the highest damage of 10.8% compared to Hemiptera (8.5%), Coleoptera (7.9), Acari (3.0%), Orthoptera (2.2%), Thysanoptera (1.3%) and Diptera (0.8%) orders.

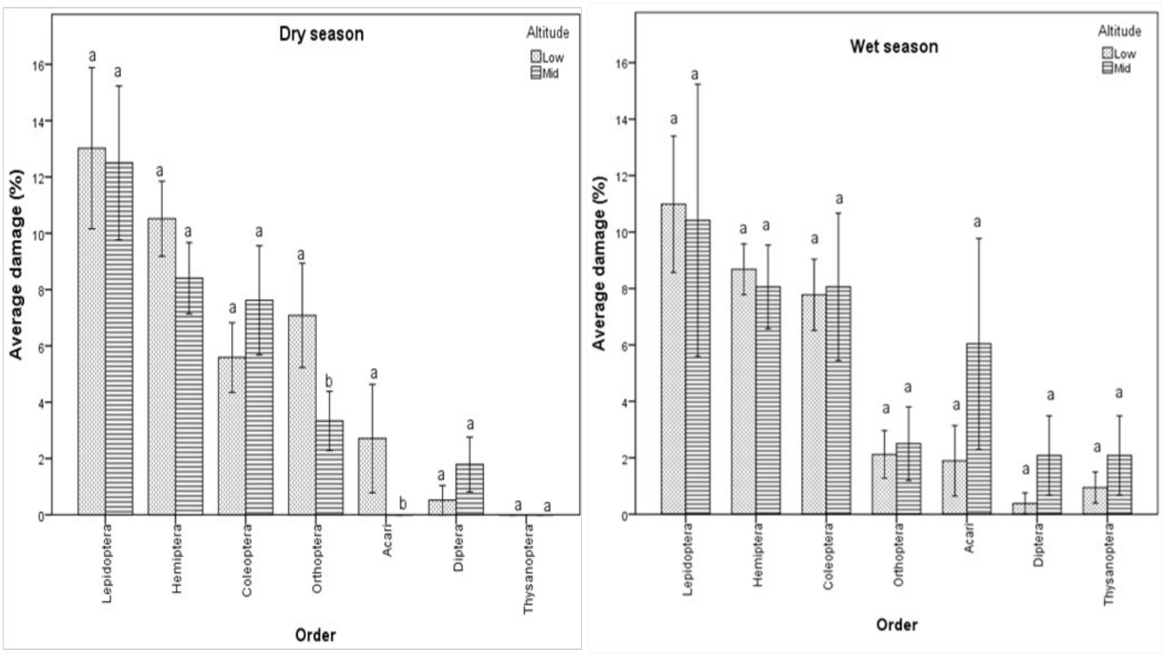

Figure 2-7: Average damage per farm of amaranth pest orders at low and mid altitude in dry (left graph) and dry season (right graph) respectively during the 2014 survey carried out in eight regions of Tanzania. (ANOVA; Means compared using Tukey test, p=0.05, n=99).

2.6 Discussion

Species diversity of arthropods in agro ecosystems such as that of amaranth farms is dependent on various factors such as climatic conditions, cropping systems, and cultural practices that alter habitat diversity. In this study, the high pest and natural enemy diversity during the post-wet season can be attributed to high crop diversities serving as food sources and hiding place for a variety of insects. This was mainly crop-weed diversity as a result of prolonged rains that caused delayed crop harvests and overgrown vegetation neighboring amaranth fields. On the other hand, the wet season was characterized by cleaner crop stands thus more homogenous plants supporting fewer pest species. Interrupted feeding and reproduction of insects by rain may explain the low species diversity observed in the wet season compared to the dry season. Mixed cropping is also a common practice among small-scale growers in Tanzania who mainly practice farming for family food and social obligations (Gardner et al., 2005). Amaranth was mainly intercropped with maize, nightshades, cucurbits, eggplants, or bananas all of which are host plants of polyphagous herbivores such as *M. persicae*, *A. gossypii,* and *A. crassivora* aphid species (Mureithi et al., 2017) that were the most abundant species during the survey.

This study found out that insects from the Lepidoptera order accounted for the highest damage on amaranth crops with up to ten species observed. Lepidopteran species *S. recurvalis*, *U. ferrugalis*, *Hepertogramma bipunctalis* and *S. litorralis* found during this study have also been reported in Kenya (Mureithi et al. 2017; Kahuthia-Gathu, 2013) and Nigeria (Aderolu et al., 2013). The presence of crops such as eggplant, beans, spinach, and maize growing near or together with amaranths might also have served as alternative hosts for polyphagous moths *H. bipunctalis* and *S. litorralis* thus their abundance. The spread of *S. recurvalis* has been attributed to its ability to adapt to a wide range of climatic conditions

(Aderolu et al., 2013). *Udea ferrugallis* larvae damage amaranth mainly on the leaves where they glue the leaves together and feed and later roll the leaves to form a secure pupation site. However, growers can use cultural practices such as farm sanitation, crop rotation (James et al., 2007), and light traps to reduce the Lepidoptera pest populations. *Apanteles sp.* a larva parasitoid of *S. recurvalis* which was also observed during the survey suppresses this pest (Othim, 2016).

Hemiptera is a diverse insect order containing numerous species of economic importance in amaranth production, particularly aphids, bugs, whiteflies, and mealybug species. The position of aphids as the most abundant pests during this survey agrees with the findings of a study on the production and consumption of AIVs in Tanzania by Keller (2004), where aphids were reported as major pests in Arumeru district. *A. fabae*, *M. persicae,* and *A. craccivora* collected during this survey have also been reported in neighboring Kenya where an additional species *Toxoptera* sp. was reported in amaranth. The three aphid species identified in this survey can transmit more than 100 viruses in 30 plant families and yield losses through viral disease could be incurred (Francki et al., 1979). Large populations of *A. colemani* a major parasitoid of aphids and voracious coccinellid beetles observed in amaranth fields can play a major role in suppressing populations. Another important pest group in the Hemiptera order was the seed-sucking bugs (Heteroptera) also known as true bugs that mostly damage seeds by inserting their stylets into the tissues and ejecting saliva before sucking the sap causing tissue necrosis. In the Coreidae family, *C. indicator* and *C. orientalis* were more in the dry season when more amaranth crops were at the flowering stage since the species prefer to feed on immature seeds. Yield losses of up to 40% have been reported in the Meru region of Kenya (Kagali et al., 2013).

Coleoptera was the third most damaging pest order during this study after Lepidoptera and Hemiptera order. The members of Coleoptera are characterized by chewing mouthparts both in larval and adult stages making them injurious herbivores. Several families were observed during the 2014 survey including stem weevil such as *H. truncatulus* that was the most abundant coleopteran species and which a destructive pest of amaranth also reported in Kenya (Kagali et al., 2013), Nigeria (Aderolu et al., 2013) and South Africa (Louw, 1995). Its larva bores into roots and stems while adults feed on leaves and petals. Other families include leaf beetles (Chrysomelidae) that make round holes in leaves, stems, and petal through their feeding, darkling beetles (Tenebrionidae) whose adults defoliate leaves and stems while the larvae feed on germinating seeds and root crops, and seed beetles (Bruchidae) that mainly bore into seeds. The high abundance of Coleoptera was highest in the mid altitude during the wet season. Wet conditions favour plant growth hence high availability food i.e. floral parts for the adults and soft stems and immature pods for the larval stages.

Tetranychus spp. were only present in the low altitude in the dry season but were not collected in the mid altitude probably due to the rains that were occurring in these zones. These weather conditions may also have contributed to a similar distribution of thrips species. *Teleogryllus sp*. in the Glyllidae family damages seedlings though it is also considered a beneficial insect for its role in feeding on organic matter and fungi.

A variety of arthropod pests damage amaranth throughout the year and therefore farmers and extension officers need to cognizant of the major pests and prioritize resources to achieve effective control. Cultural practices such as field hygiene need to be emphasized to eradicated pest from previous crop or neighboring fields before planting whereas, during crop growth, pest control will need to focus on effective management strategies for each pest group.

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3 Diversity and distribution of arthropod pests of African nightshade and their associated natural enemies in Tanzania

3.1 Abstract

African nightshade is an important traditional vegetable in East Africa for its high nutritional value and as a source of income. However, arthropod pests are a major challenge in its production. To identity the pests of nightshades and their natural enemies, their distribution, and diversity a survey was carried out in different regions over two seasons in Tanzania. The major pests of African nightshades were the red spider mites (Acari) causing 11%, twice (5%) the damage caused by aphids (Hemiptera), and three times (3%) that of beetles (Coleoptera). Other pest orders were Diptera causing 2% leaf damage, Lepidoptera, Orthoptera, and Thysanoptera each causing almost 1% damage. Hymenopteran species, mainly aphid parasitoid *Aphidius colemani*, coccinellid beetles (Coleopterans), and predatory mites (Mesostigmata) were the most abundant natural enemy species. Mid altitude regions had higher diversity with 77species while there were 60species in the low altitude. These findings will assist farmers and service providers to prioritize pest management resources according to the importance of the pest groups.

Key words: Indigenous vegetables, guilds, pest status, seasonal abundance, pest management

3.2 Introduction

The African nightshades are a group of *Solanum* spp. of African origin that has gained great popularity among African communities as nutritious leafy vegetables (Muhanjai, et al., 2011; Weinberger & Swai, 2006). Species commonly used are *S. villosum*, *S. Scabrum*, *S. americanum*, *S. sarrachoides* (Schippers, 2002). The leaves are rich sources of vitamins A, B and C, proteins, minerals such as Iron, Calcium, Iodine, Phosphorus, Zinc and also have medicinal properties (Ochieng et al., 2007). In Tanzania, the vegetable is the most marketed and consumed and therefore considered important in combating nutritional and health issues particularly for the poor households (Weinberger & Swai, 2006).

However, African nightshades are damaged by various arthropod pests (Mureithi et al., 2017). Aphids and red spider mites are particularly destructive during the dry season causing up to 100% yield loss (Keller, 2004). Other pests reported on nightshades include whiteflies, black aphids (*Aphis fabae*), leaf miners (*Lyriomyza* spp), leafhoppers, flea beetles (*Chrysomelidae* spp), Root-knot nematodes (*Meloidyne* spp), African bollworm (*Helicoverpa armigera*), Systates weevils grasshoppers (*Systates pollinosus*), and cutworms (Agrotis spp) (Kipkosgei, 2004).

The destructive pest status of arthropods is dynamic and changes with the season, year, country, plant species, variety, cultivar, and cropping systems (Reddy, 2017). Therefore it is important to identify pest species and estimate their crop damage to allocate pest management resources based on the relative importance of each pest (Kular & Kumar, 2011). Also, it is important to understand the species diversity during different production season to understand the pest and natural enemy's communities present. Diversity indices such as species richness and evenness are used to compare the species diversity in different areas (Morris et al., 2014).

However, despite the importance of African nightshade as a nutritious vegetable that can combat malnutrition in poor communities in Tanzania (Ochieng et al., 2016) information on pests of African nightshade is scanty. This study was undertaken in Tanzania to identify the diversity of arthropod species, the main damaging arthropods pests of African nightshade, and their natural enemies along different altitudes and seasons. The study will provide information on major pest species of African nightshades and assist to prioritize pest management resources according to the importance of the pest.

3.3 Methodology

The methods used are as described in chapter 2.4.

3.4 Results

3.4.1 Abundance of arthropods in African nightshades

In this study, a total of 80 species from 38 families and 11 orders were identified as pests and natural enemies associated with the African nightshade. Among these were 54 pest species from 27 families and 7 orders. These orders include Coleoptera, Diptera, Hemiptera, Lepidoptera, Orthoptera, Thysanoptera, and Acari (Table 3-1).

Table 3-1: Composition and abundance of pest species observed in African nightshade fields during the 2014 survey in Tanzania, n=95

Order	Family	Species	Mean±SE insects/plant/farm	Relative abundance
Acari	Tetranychidae	*Tetranychus evansi*	8.994±2.026	78.19%
Acari	Tetranychidae	*Tetranychus urticae*	1.431±0.738	12.44%
Hemiptera	Aphididae	*Aphis fabae*	0.965±0.186	4.19%
Hemiptera	Aphididae	*Aphis craccivora*	0.445±0.119	1.94%
Hemiptera	Aphididae	*Myzus persicae*	0.401±0.101	1.74%
Hemiptera	Aleyrodidae	*Bemisia tabaci*	0.064±0.024	0.28%
Thysanoptera	Thripidae	*Megalurothrips sjostedti*	0.024±0.016	0.15%
Thysanoptera	Thripidae	*Haplothrips cahirensis*	0.013±0.008	0.10%
Coleoptera	Chrysomelidae	*Phyllotreta* sp.	0.019±0.005	0.08%
Diptera	Agromyzidae	*Lyliomyza* sp.	0.019±0.004	0.08%
Lepidoptera	Gelechiidae	*Tuta absoluta*	0.006±0.002	0.06%
Hemiptera	Lygaeidae	*Nysius binotatus*	0.011±0.005	0.05%
Lepidoptera	Noctuidae	*Helicorvepa armigera*	0.001±0.001	0.05%
Hemiptera	Pentatomidae	*Nezara viridula*	0.008±0.003	0.04%
Lepidoptera	Crambidae	*Psara bipunctalis*	0.005±0.002	0.04%
Lepidoptera	Lepidoptera	*Agrotis* sp.	0.002±0.002	0.04%
Orthoptera	Acrididae	*Dichromorpha* sp.	0.001±0.000	0.04%
Orthoptera	Pyrgomorphidae	*Pyrgomorphella albini*	0.005±0.003	0.04%
Coleoptera	Chrysomelidae	*Epitrix siluicola*	0.008±0.004	0.03%
Coleoptera	Tenebrionidae	*Lagria villosa*	0.007±0.003	0.03%
Diptera	Diopsidae	*Diopsis servillei*	0.006±0.003	0.03%
Thysanoptera	Thripidae	*Frankliniella Schultzei*	0.003±0.003	0.03%
Thysanoptera	Thripidae	*Haplothrips gowdeyi*	0.002±0.002	0.03%
Coleoptera	Brentidae	*Apion* sp.	0.005±0.001	0.02%
Coleoptera	Tenebrionidae	*Lagria cuprica*	0.003±0.002	0.02%
Hemiptera	Lygaeidae	*Graptostethus electus*	0.002±0.002	0.02%
Hemiptera	Lygaeidae	*Nysius* sp.	0.005±0.002	0.02%
Hemiptera	Pentatomidae	*Asparia armigera*	0.005±0.002	0.02%
Lepidoptera	Noctuidae	*Spodoptera exigua*	0.002±0.002	0.02%
Orthoptera	Acrididae	*Schistocerca gregaria*	0.003±0.001	0.02%
Coleoptera	Anthicidae	*Formicomus* sp.	0.003±0.002	0.01%
Coleoptera	Chrysomelidae	*Hypolixus truncatulus*	0.001±0.001	0.01%
Coleoptera	Curculionidae	*Baris* sp.	0.001±0.001	0.01%
Coleoptera	Curculionidae	*Lixus rhomboidalis*	0.003±0.001	0.01%
Coleoptera	Curculionidae	*Systates crenatipennis*	0.002±0.001	0.01%
Coleoptera	Meloidae	*Epicauta albovita*	0.002±0.001	0.01%
Coleoptera	Tenebrionidae	*Lagria cyanicollis*	0.001±0.001	0.01%
Hemiptera	Coreidae	*Cletus indicator*	0.003±0.001	0.01%
Hemiptera	Coreidae	*Cletus orientalis*	0.002±0.001	0.01%
Hemiptera	Pentatomidae	*Bagrada hilaris*	0.003±0.002	0.01%
Hemiptera	Reduviidae	*Rhinocoris* sp.	0.002±0.001	0.01%

Order	Family	Species	Mean±SE insects/plant/farm	Relative abundance
Lepidoptera	Crambidae	*Udea ferrugalis*	0.001±0.001	0.01%
Lepidoptera	Plutellidae	*Plutella xylostella*	0.001±0.001	0.01%
Lepidoptera	Pyralidae	*Psara atritermina*	0.001±0.001	0.01%
Orthoptera	Gryllidae	*Teleogryllus* sp.	0.001±0.000	0.01%
Orthoptera	Pyrgomorphidae	*Phymateus viridipes*	0.000±0.000	0.01%
Orthoptera	Pyrgomorphidae	*Zonocerus elegans*	0.001±0.001	0.01%
Coleoptera	Aderidae	*Hylophilus* sp.	0.001±0.001	< 0.01%
Coleoptera	Curculionidae	*Babaultia* sp.	0.001±0.000	< 0.01%
Coleoptera	Melyridae	*Melyris parvula*	0.001±0.001	< 0.01%
Hemiptera	Coreidae	*Acanthocoris fasciata*	0.001±0.001	< 0.01%
Hemiptera	Pentatomidae	*Antestia* sp.	0.001±0.001	< 0.01%
Lepidoptera	Noctuidae	*Spodoptera exempta*	0.000±0.000	< 0.01%
Lepidoptera	Noctuidae	*Spodoptera litorralis*	0.000±0.000	< 0.01%

3.4.2 Abundance of spider mite pests associated with African nightshade

There was a difference ($F_{(1, 124)}$ =12.55, p>0.001) in the number of mite per plant per farm between *T. evansi* (11.31±2.20) and *T. urticae* (2.74±1.03), the two species found in African nightshade. *T. evansi* accounted for 80.5% of the total mites while *T. urticae* accounted for 19.5%. During the two seasons and altitudes, *T. evansi* was the most abundant species (Figure 3-1). However, there were no differences in total mite populations between seasons ($F_{(1, 124)}$ =0.49, p=0.48) with a mean±SE of 8.36±2.26 and 5.78±1.17mites per plant per farm in the dry and wet seasons respectively. Mites from the dry season accounted for 57.6% of total mite samples while the wet season accounted for 42.4%. Also, there was no significant difference between altitudes ($F_{(1, 124)}$ =2.37, p=0.126) with mites in the low altitude (9.35±2.37) accounting for 64.4% of the total mites samples while those from mid altitude (4.85±1.02) accounted for 35.6%.

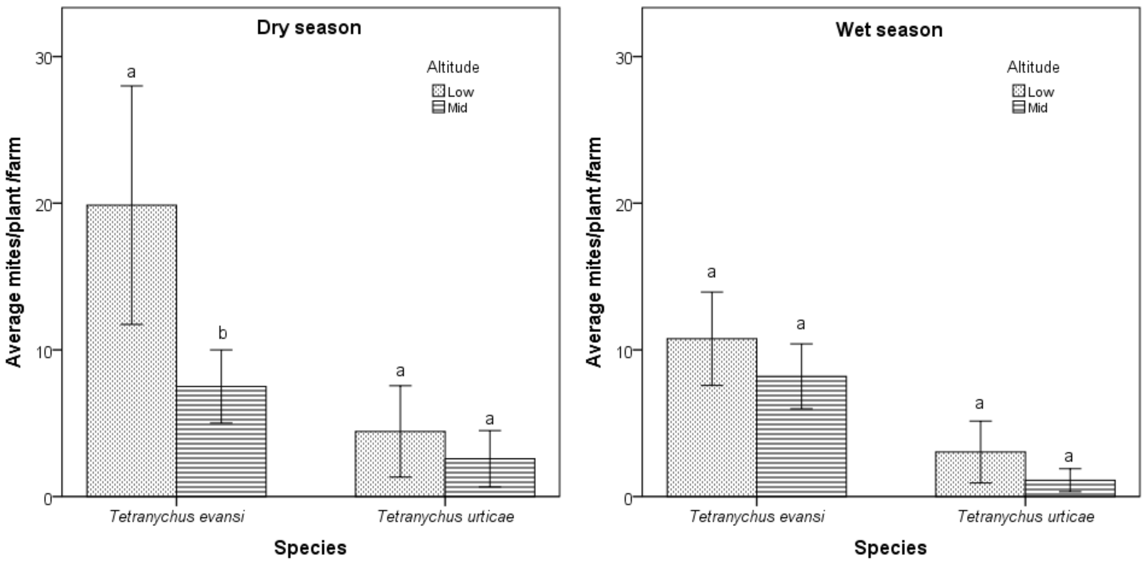

Figure 3-1: Means of *T. evansi* and *T. urticae* per plant per Amaranth farm in low and mid altitude regions of Tanzania during the dry (left graph) and wet season (right graph) in 2014. (ANOVA; Means compared using Tukey test, p=0.05, n=95)

3.4.3 Abundance of aphid pests in African nightshades

There was a difference ($F_{(2, 186)}$ =5.47, p=0.005) in the number of aphids per plant per farm with *A. fabae* (0.95±0.19) having a higher population (53.3%) than *A. craccivora* (0.45±0.11) and *Myzus persicae* (0.40±0.10) each accounting for 24.6% and 22.2% respectively. *A. fabae* remained dominant across the dry and wet seasons as well as low and mid altitudes (Figure 3-2). However, there were no differences in total aphids populations between seasons ($F_{(1, 186)}$ =2.38, p=0.13) with a Mean±SE of 0.72±0.14 and 0.49±0.09 aphids per plant per farm in the dry and wet seasons respectively. Aphids from the dry season accounted for 57.7% of total aphid samples while the wet season accounted for 42.3%. Also, there was a significant difference between altitudes ($F_{(1, 186)}$ =4.82, p=0.03) with aphids in the low altitude (0.42±0.10) accounting for 33.6% of the total aphids samples while those from mid altitude (0.78±0.13) accounted for 66.4%.

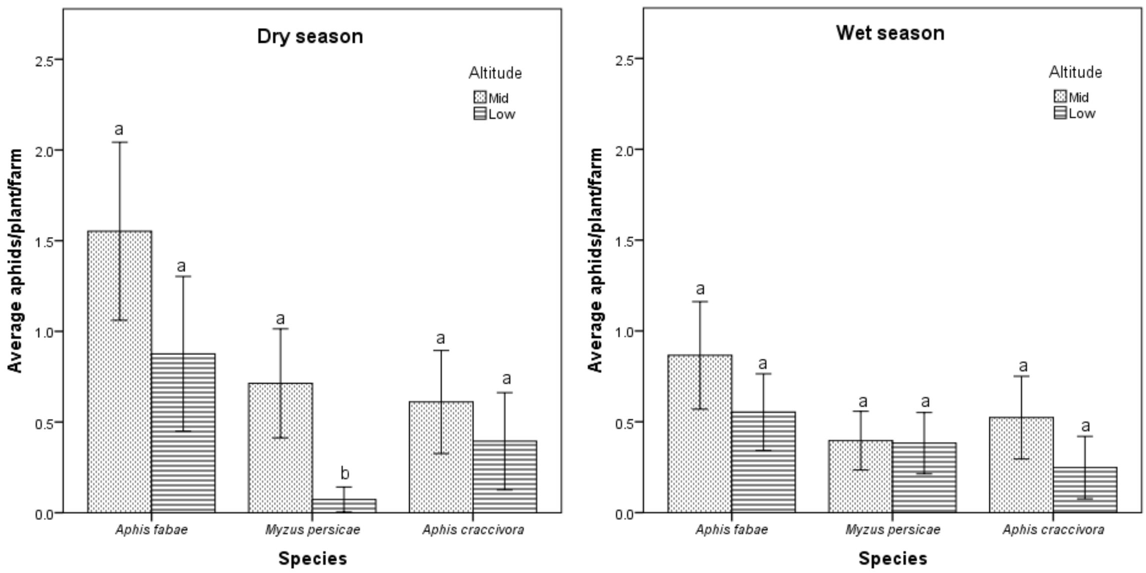

Figure 3-2: Mean of *A. fabae*, *A. crassivora,* and *M. persicae* per plant per African nightshades farm in the low and mid altitude regions of Tanzania during the dry season (left graph) and wet season (right graph) in 2014. (ANOVA; Means compared using Tukey test, p=0.05, n=95)

3.4.4 Abundance of natural enemies of African nightshade pests

There were 26 species of natural enemies collected during the survey. The species were from 11 families in 7 orders. The most species (14) were coleopterans with 13 being Coccinellids. The braconid wasp, *A. colemani* known to parasitize on aphids was the most abundant species (Table 3-2).

Table 3-2: Composition and abundance of natural enemy species in African nightshade fields during the 2014 survey in Tanzania, n=95.

Order	Family	Species	Mean±SE insects/ plant/farm	Relative abundance
Hymenoptera	Braconidae	*Aphidius colemani*	0.134±0.014	63.50%
Mesostigmata	Phytoseiidae	*Phytoseiulus* sp.	0.012±0.001	5.40%
Hemiptera	Pynhocoridae	*Dysdereus fasciatus*	0.009±0.001	4.00%
Coleoptera	Coccinellidae	*Scymnus trepidulus*	0.008±0.000	3.80%
Coleoptera	Coccinellidae	*Cheilomenes sulphurea*	0.008±0.001	3.60%
Coleoptera	Coccinellidae	*Scymnus kibonotensis*	0.007±0.001	3.20%
Coleoptera	Coccinellidae	*Cheilomenes aurora*	0.005±0.001	2.20%
Coleoptera	Coccinellidae	*Brumoides fulviventris*	0.004±0.000	2.00%
Coleoptera	Coccinellidae	*Scymus casstroemi*	0.004±0.000	1.70%
Coleoptera	Coccinellidae	*Hippodamia variegata*	0.003±0.000	1.20%
Mesostigmata	Phytoseiidae	*Amblyseius* sp.	0.003±0.000	1.20%
Odonata	Coenagrionidae	*Africallagma elongatum*	0.003±0.000	1.20%
Neuroptera	Chrysopidae	*Chrysoperla carnea*	0.002±0.000	1.00%
Coleoptera	Coccinellidae	*Scymnus pruinosus*	0.002±0.000	0.70%
Diptera	Syrphidae	*Syrphid* sp.	0.002±0.000	0.70%
Hymenoptera	Formicidae	*Polyrhachis* sp.	0.002±0.000	0.70%
Coleoptera	Coccinellidae	*Scymnus levaillanti*	0.001±0.000	0.60%
Diptera	Anthocoridae	*Orius* sp.	0.001±0.000	0.60%
Diptera	Cecidomyiidae	*Aphidoletes aphidimyza*	0.001±0.000	0.60%
Coleoptera	Coccinellidae	*Henosepilachna hirta*	0.001±0.000	0.50%
Coleoptera	Staphylinidae	*Paederus riftensis*	0.001±0.000	0.50%
Hymenoptera	Formicidae	*Crematogaster sp.*	0.001±0.000	0.20%
Coleoptera	Coccinellidae	*Micraspis* sp.	0.000±0.000	0.10%
Coleoptera	Coccinellidae	*Platynaspis sexguttata*	0.000±0.000	0.10%
Coleoptera	Coccinellidae	*Scymnus morelleti*	0.000±0.000	0.10%
Odonata	Coenagrionidae	*Africallagma subtile*	0.000±0.000	0.10%

3.4.5 Diversity of arthropod pests and their natural enemies in African nightshades

The mid altitude diversity profile in the dry season was above that of low altitude indicating higher arthropod species diversity in the mid altitude (Figure 3-3). However, in the wet season, the diversity profiles of low and mid altitudes touch with similar values of species evenness indicating there was no difference in diversity between the two altitudes (Figure 3-3). Species richness indicated by H-alpha value at alpha=0 was different between altitudes in the dry season but the similar wet season. The x-axis shows an increase in the weight of dominant species in the diversity profile, where at 0 all species have equal weight while at infinity only the most dominant species account for the diversity index value.

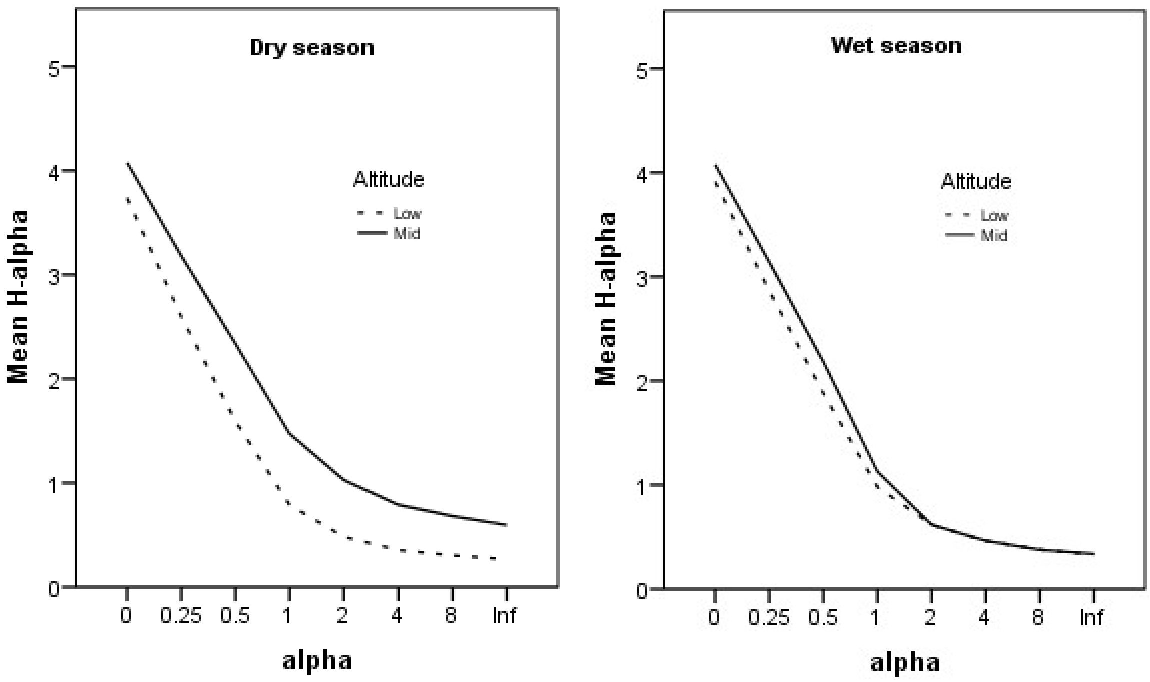

Figure 3-3: Renyi diversity profiles for African nightshade pests and their associated natural enemies in the low and mid altitude zones during the dry season (left graph) and wet season (right graph) of 2014 survey carried out in eight regions of Tanzania.

3.4.6 Damage caused by pest orders in African nightshade

There was an interaction ($F_{(8,\ 2762)}$ =3.23, p=0.004) between pest orders and altitude in leaf damage with pest orders being significantly different ($F_{(8,\ 2762)}$ =61.70, p>0.001). The red spider mites order (Acari) was the most damaging order causing 10.8% leaf damage. This was twice the damage caused by Hemiptera (4.94±0.58) and Coleoptera (3.33±0.53) as the second and third most damaging orders respectively. Other pest orders observed were in their order of damage were beetles (Coleoptera), leaf miners (Diptera), moth (Lepidoptera), thrips (Thysanoptera), and grasshoppers (Orthoptera) as presented in Figure 3-5.

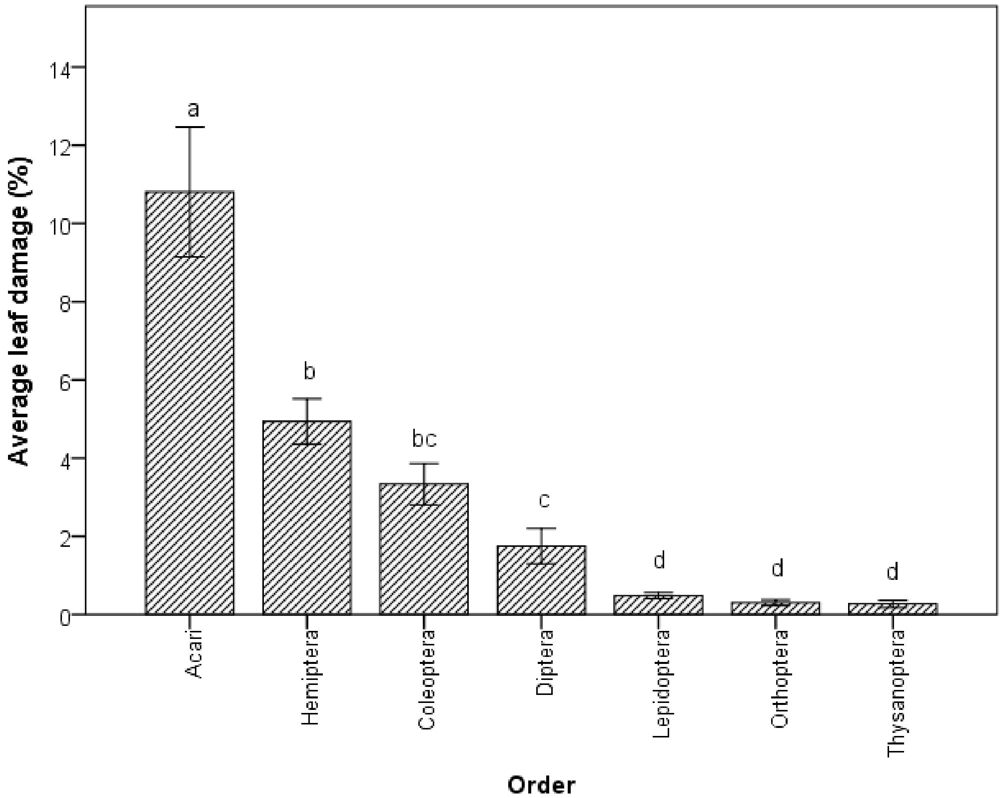

Figure 3-5. Leaf damage caused by pest orders associated with African nightshade in Tanzania during the dry and wet season in 2014. (ANOVA; Means compared using Tukey test, p=0.05, n=95)

The damage caused by coleopterans and hemipterans pest species was different between the altitudes. For the coleopteran, the mid altitude regions suffered twice the damage in the low altitude regions with average leaf damage of 4.44±0.84 and 2.15±0.6 respectively. Also, Hemipterans caused higher damage in the mid altitudes with an average damage of 5.86±0.88 compared to 3.96±0.73 in the low altitude regions. A similar trend was observed during the dry season (Figure. 3-6).

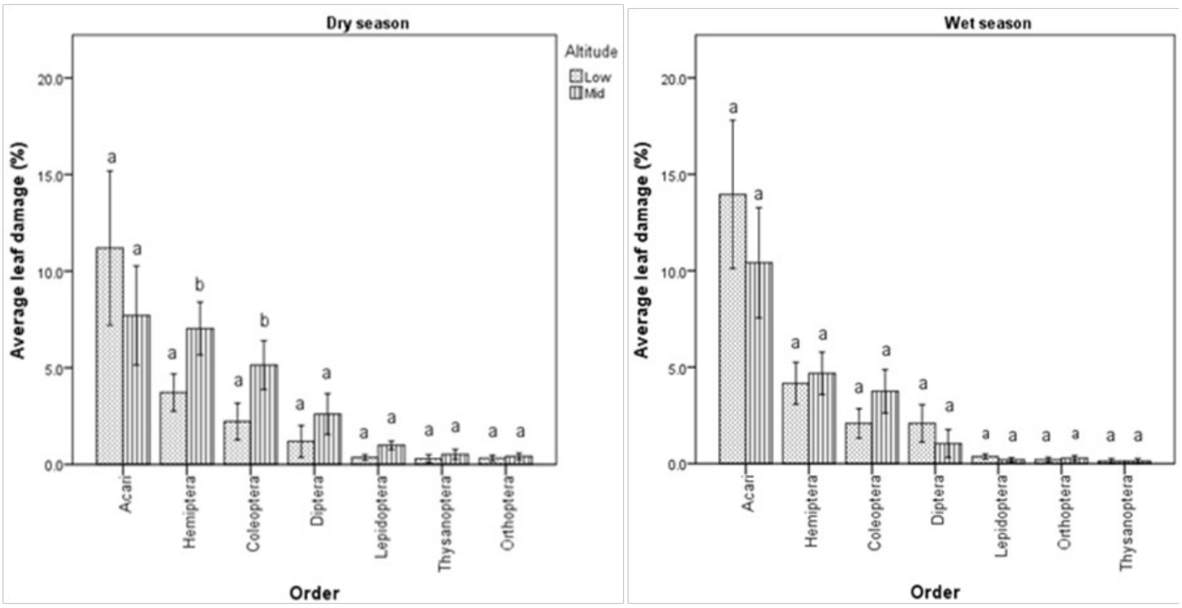

Figure 3-6: Average damage of pest orders of African nightshade per farm in low and mid-altitude zones during the dry season (left graph) and wet season (right graph) of the 2014 survey carried out in eight regions of Tanzania. (ANOVA; Means compared using Tukey test, p=0.05, n=95).

3.5 Discussion

In this study, the diversity of arthropod species was higher in mid altitudes regions compared to low altitude regions. Mid altitude regions were characterized by high rainfall and moderate temperatures that supported diverse plant communities. In a review by (Tews et al., 2004) they found that in most studies there was a positive correlation between habitat heterogeneity and animal species diversity, particularly in arthropods. The extent of ground cover also affects the occurrence of certain arthropods. This is particularly important to beetles where plant debris, logs, or rocks provide refuge from predators and facilitate foraging (Lassau et al., 2010). This may explain the high abundance of flea beetle species in the mid altitudes where vegetation and litter heterogeneity was high. The low species evenness observed in the low altitude indicates that only a few species such as red spider mites and aphids dominate the arthropod community. This might be attributed to the fact that in areas with high pest infestations; farmers may use pesticides more often thus killing non-target insects including natural enemies of the pest. In the long run, such a scenario would lead to the development of resistance to pesticides and a rapid increase in populations of the pest. In this study, red spider mites were the most damaging pests of African nightshades with the tomato red spider mite, *T. evansi* species being the dominant species in the study regions. These findings, confirm that *T. evansi* has spread from where it was first reported by Boubou and his colleagues in 2011. In their study, they reported *T. evansi* in several Solanum samples including *S. lycopersicum* from Simba Hills in Kwale, *S. nigrum*, *S. aethiopicum*, *S. lycopersicum* and *S. stramonium* in AVRDC in Arusha, *S. tuberosum* in Lushoto, and *S. aethiopicum* in Morogoro, Mukuyuni (Boubou et al., 2011). Similarly, we observed that apart from African nightshades, farmers also grew other Solanaceous crops such as tomatoes and African eggplants in adjacent fields. Therefore, the availability of other host plants may have contributed to the high mite infestations observed. *T. evansi* populations were twice in the dry season compared to the wet season particularly in the low altitude regions of Pwani and Kilimanjaro. Similar observations were reported in the Tabora region of Tanzania, where *T. evansi* is considered a major threat to dry season tomato production (Bagarama, 2014). In this study, flea beetles were observed to cause considerable leaf damage in Lushoto district in the low altitude region. Similar concurs with the findings of (Mureithi, 2018) where beetles damage was higher in mid altitude areas in Kenya. These findings that certain pest species are important across regions while others are in certain regions can assist farmers to be more vigilant and closely monitor the occurrence of such pests.

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4 Distribution and diversity of insect pests of Ethiopian kale and their natural enemies in Tanzania

4.1 Abstract

Insect pests cause enormous losses in Ethiopian kale, an African indigenous vegetable. Accurate identification of pests is a key component in effective pest management. However, information on the major pests of Ethiopian kale is scanty within East Africa. A survey was carried out in Tanzania during the dry and wet seasons of 2014 to determine insect diversity in Ethiopian kale fields and identify the main damaging pests and their associated natural enemies. Species diversity in the low and mid altitudes regions was not different during the wet and dry seasons. Hemipterans were the most damaging pests causing 30% and 16% leaf damage during the dry and wet season respectively. Among the hemipterans, *Brevicoryne brassicae* was the most abundant species in the mid-altitudes while *Myzus persicae* was abundant in the low-altitudes. Lepidopterans caused 24.9% and 14.7% leaf damage in the dry and wet season respectively. Among lepidopterans, *Plutella xylostella* was the most abundant (77.2%) species while *Agrotis ipsilon* and *Psara atritermina* accounted for 10.4% and 8% respectively. The aphid parasitoid, *Diaeretiella rapae* (Hymenoptera), and coccinellid beetles (Coleoptera) such as *Scymnus* spp. and *Cheilomenes* spp. were the most abundant natural enemies. The information generated in this study will assist in ranking pests and developing management pest infestation Ethiopian kale farms.

Key words: Guilds, leaf damage, species abundance, *Brassica carinata*, biological control

4.2 Introduction

Brassica carinata (A. Braun), Ethiopian kale is a crop grown and consumed in Africa as a vegetable (Adeniji & Aloyce, 2014; Grzywacz et al., 2010). The leaves, tender stems, and flowers are used as vegetables, have high nutritional value (Shackleton et al., 2009), and are reported to contain cancer preventative compounds (Odongo et al., 2017). The plant originated from the Ethiopian Plateau and in Tanzania, the vegetable is locally known as Loshuu or Figiri and some of the common varieties cultivated in the country are the Mbeya green and Lambo (Schippers, 2002). However, the plant is also cultivated as an oilseed crop in Africa, Asia (Kular & Kumar, 2011), USA, and Europe (Seepaul et al., 2016). Its seeds yield more than 40% oil although it is not edible due to high levels of undesirable erucic acid and glucosinolates. However, the oil is suitable for industrial uses such as biodiesel and chemical additives in plastic, tannery, and cosmetics (Bozzini et al., 2007). Moreover, new cultivars containing low levels of erucic acid have been developed for the production of edible oil (Velasco et al., 2004). Agronomically, Ethiopian kale is a superior Brassica crop that sets seed in warmer tropical temperatures unlike most Brassica crops, it is tolerant to heat, drought, salinity, and frost. The crop is also tolerant to plant pathogens such as the causal agent for blackleg; *Leptosphaeria maculans* (Gugel et al., 1990), black rot and white rust; *Albugo candida* (Singh and Singh, 1988), reduces nematodes (Brown, 2005) and suppresses weeds (Seepaul et al., 2016).

However, insect pests are a major challenge to farmers of Ethiopian kale (Adeniji & Aloyce, 2014); (Keller, 2004). The major insect groups that damage Ethiopian kale are defoliators such as caterpillars, beetles, grasshoppers, and sucking insects that include: aphids, whiteflies, bugs, and whiteflies. Diamondback moth, (*Plutella xylostella* (Linnaeus)), cabbage sawfly (*Anthalia sjostedti* (Trybom)), Cabbage looper (*Trichoplusia ni* (Hübner)), and tomato leaf miner (*Tuta absoluta*), are lepidopteran species whose larva defoliate the plant. Hemiptera order contains the sap-sucking pests such as cabbage aphid (*Brevicoryne brassicae* (Linnaeus)), green peach aphid (*Myzus persicae* (Sulzer)), cabbage whiteflies (*Aleyrodes proletella* (Linnaeus)), mealybugs (Pseudococcidae family), and bagrada bugs (*Bagrada hillaris* (Bermeister)). Coleopteran pests include flea beetles (*Phyllotreta* spp.).

Therefore taking into account that the destructive pest status of insects is dynamic and changes with season, year, altitudes, plant species, variety, cultivar, and cropping systems (Reddy, 2017), it is important to characterize insect pests and estimated crop damage to allocate pest management resources based on the relative importance of each pest (Kular & Kumar, 2011). To achieve this, understanding the species diversity in the fields is important to establish the pest and natural enemy communities present. This study was carried out to identify the main damaging pests of Ethiopian kale and their natural enemies in Tanzania. Species diversity of Ethiopian kale pests and their natural enemies was also assessed across different altitudes during the two main growing seasons to assist in prioritizing pest management according to pest species.

4.3 Methodology

The methods used are as described in chapter 2.4.

4.4 Results

4.4.1 Abundance of insect pests in Ethiopian kale

There were 56 pest species from 30 families in 7 orders while. In this study pest species from 7 orders and 32 families were observed. Hemiptera was the most diverse and abundant pest order with 23 species that included aphids, stink bugs, beetles, whiteflies, and mealybugs. Aphididae was the most abundant accounting for 90.6% of the total individuals in the order.

The 14 pest species observed in the order Coleoptera included ladybirds, weevils, and flower beetles. Lepidoptera had 7 pest species mainly the Diamondback moth, webworms, and cutworms. 5 grasshopper species were observed in the Orthoptera order. Thysanoptera had 4 thrips species while there was one species each for leaf miner and stalk-eyed fly in Diptera order and Hymenoptera with 2 ant species (Table 4-1).

Table 4-1: Composition and abundance of pest species observed in Ethiopian kale fields during the 2014 survey in Tanzania. Abundance as mean insects per plant per farm, n=80.

Order	**Family**	**Species**	**Mean±SE insects/ plant/farm**
Hemiptera	Aphididae	*Brevicoryne brassicae*	0.548±0.320
Hemiptera	Aphididae	*Myzus persicae*	0.491±0.287
Lepidoptera	Plutellidae	*Plutella xylostella*	0.134±0.033
Hemiptera	Aleyrodidae	*Aleyrodes proletella*	0.048±0.022
Hemiptera	Aleyrodidae	*Bemisia tabaci*	0.031±0.008
Hemiptera	Pentatomidae	*Bagrada hilaris*	0.022±0.011
Lepidoptera	Noctuidae	*Agrotis ipsilon*	0.018±0.008
Diptera	Diopsidae	*Diopsis servillei*	0.017±0.004
Thysanoptera	Thripidae	*Megalurothrips sjostedti*	0.011±0.006
Lepidoptera	Crambidae	*Psara atritermina*	0.011±0.004
Hemiptera	Aphididae	*Aphis fabae*	0.008±0.004
Hemiptera	Aleyrodidae	*Aleurothrixus floccosus*	0.007±0.003
Coleoptera	Chrysomelidae	*Lema ornatula*	0.006±0.006
Thysanoptera	Thripidae	*Sericothrips sp.*	0.005±0.005
Hemiptera	Pentatomidae	*Nezara viridula*	0.005±0.003
Hemiptera	Miridae	*Mirid* sp.	0.005±0.002
Hemiptera	Pentatomidae	*Pentatomid* sp.	0.005±0.002
Lepidoptera	Crambidae	*Spoladea recurvalis*	0.004±0.002
Hemiptera	Lygaeidae	*Nysius binotatus*	0.003±0.002
Lepidoptera	Crambidae	*Hellula undalis*	0.003±0.001
Lepidoptera	Gelechiidae	*Tuta absoluta*	0.003±0.001
Thysanoptera	Thripidae	*Haplothrips cahirensis*	0.003±0.001
Coleoptera	Chrysomelidae	*Phyllotreta* sp.	0.002±0.002
Thysanoptera	Thripidae	*Scirtothrips dorsalis*	0.002±0.002
Coleoptera	Curculionidae	*Baris* sp.	0.002±0.001
Coleoptera	Tenebrionidae	*Lagria cyanicollis*	0.002±0.001

Order	**Family**	**Species**	**Mean±SE insects/ plant/farm**
Hemiptera	Coreidae	*Cletus orientalis*	0.002±0.001
Hemiptera	Pyrrhocoridae	*Dysdercus fasciata*	0.002±0.001
Hymenoptera	Formicidae	*Polyrhachis* sp.	0.002±0.001
Orthoptera	Gryllidae	*Teleogryllus* sp.	0.002±0.001
Orthoptera	Pyrgomorphidae	*Zonocerus elegans*	0.002±0.001
Coleoptera	Anthicidae	*Formicomus spatulatus*	0.001±0.001
Coleoptera	Anthicidae	*Formicomus* sp.	0.001±0.001
Coleoptera	Brentidae	*Apion* sp.	0.001±0.001
Coleoptera	Chrysomelidae	*Epitrix sylvicola*	0.001±0.001
Coleoptera	Chrysomelidae	*Hapsidolema nigroparallela*	0.001±0.001
Coleoptera	Chrysomelidae	*Bruchus* sp.	0.001±0.001
Coleoptera	Curculionidae	*Lixus* sp.	0.001±0.001
Coleoptera	Tenebrionidae	*Allecula* sp.	0.001±0.001
Coleoptera	Tenebrionidae	*Lagria villosa*	0.001±0.001
Diptera	Agromyzidae	*Liliomyza* sp.	0.001±0.001
Hemiptera	Cercopidae	*Locris* sp.	0.001±0.001
Hemiptera	Coreidae	*Acanthomia* sp.	0.001±0.001
Hemiptera	Coreidae	*Cletus* sp.	0.001±0.001
Hemiptera	Pentatomidae	*Asparia armigera*	0.001±0.001
Hemiptera	Pentatomidae	*Antestia* sp.	0.001±0.001
Hemiptera	Pseudococcidae	*Pseudococcus* sp.	0.001±0.001
Hymenoptera	Tenthredinidae	*Athalia sjostedti*	0.001±0.001
Lepidoptera	Noctuidae	*Helicorvepa armigera*	0.001±0.001
Orthoptera	Acrididae	*Dichromorpha* sp.	0.001±0.001
Orthoptera	Acrididae	*Schistocerca gregaria*	0.001±0.001
Orthoptera	Pyrgomorphidae	*Pyrgomorphella albini*	0.001±0.001
Coleoptera	Meloidae	*Epicauta albovitatta*	0.001±0.000
Hemiptera	Lygaeidae	*Graptostethus electus*	0.000±0.000
Hemiptera	Lygaeidae	*Lygaeid* sp.	0.000±0.000
Hemiptera	Scutellaridae	*Sphaerocoris annulus*	0.000±0.000

4.4.2 Abundance of aphid species in Ethiopian kale

The aphid species identified were *B. brassicae*, *M. persicae,* and *Aphis fabae* (Glover). The abundance of the aphid species was different between seasons (p=0.02). During the dry season, there were no significant differences between low and mid-altitude abundance for *A. gossypii* (t=1.31, df=40, p=0.20), *B. brassicae* (t=0.74, df=40, p=0.47) or *M. persicae* (t=0.62, df=40, p=0.11) as illustrated in Figure 4. During the wet season, *A. gossypii* was absent and there was no significant difference in the abundance *B. brassicae* (t=0.70, df=38, p=0.47) or *M. persicae* (t=1.64, df=38, p=0.11) between low and mid altitudes (Figure 4-1).

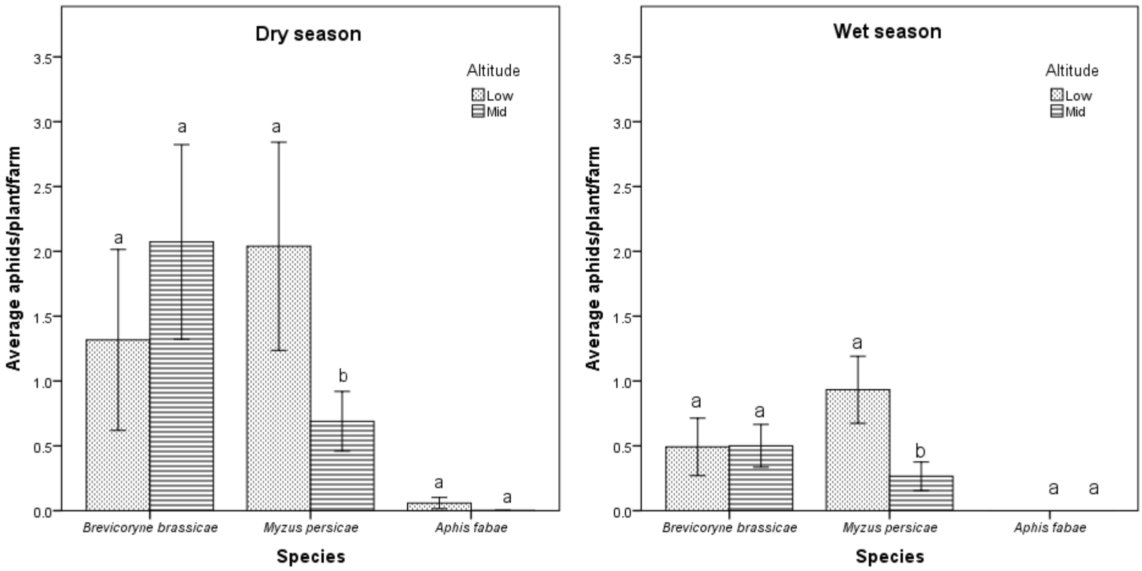

Figure 4-1: Mean of *B. brassicae*, *M. persicae* and *A. fabae* per plant per Ethiopian kale farm in the low and mid altitude regions of Tanzania during the dry season (left graph) and wet season (right graph) in 2014. (ANOVA; Means compared using Tukey test, p=0.05, n=80).

4.4.3 Abundance of Lepidoptera species in Ethiopian kale

There was a significant difference in abundance between species ($F_{(6, 532)} = 14.95$, $p<0.001$). However, there were no significant differences between seasons ($F_{(1, 532)} = 1.27$, $p=0.26$) or altitudes ($F_{(1, 532)} = 0.86$, $p=0.36$). The most abundant species were *P. xylostella* accounting for 77.2% of the total insects in the order with a mean of 0.13±0.03 insects per plant. When the abundance of the three most abundant species was compared between low and mid altitudes, there were no differences in *P. xylostella* (t=0.13, df=40, p=0.90), *A. ipsilon* (t=0.37, df=40, p=0.97) or *P. atritermina* (t=0.708, df=40, p=0.49) in dry season. Similarly, there were no significant differences in abundance between low and mid-altitude in wet season for *A. ipsilon* (t=0.0, df=38, p=1) and *P. atritermina* (t=0.83, df=38, p=0.41) but there was a difference in *P. xylostella* (t=0.15, df=38, p=0.03) as shown in Figure 4-2.

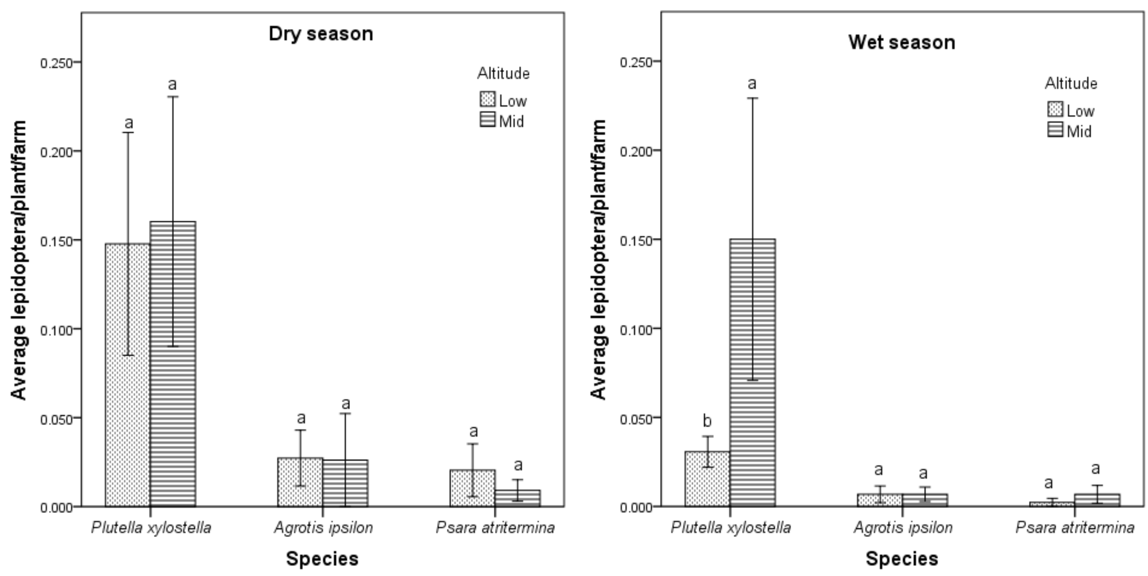

Figure 4-2: Means of *P. xylostella*, *A. ipsilon* and *P. atritermina* per plant per Ethiopian kale farm in the low and mid altitude regions of Tanzania during the dry (left graph) and wet season (right graph) in 2014. (ANOVA; Means compared using Tukey test, p=0.05, n=80).

4.4.4 Abundance of insect natural enemies in Ethiopian kale

There were 30 species of natural enemies from 12 families in 5 orders identified during this study. The most abundant natural enemies were parasitoids in the Hymenoptera order. However, most species were coccinellid beetles in the Coleoptera order (Table 4-2).

Table 4-2: Composition and abundance of natural enemy species in Ethiopian kale fields within Tanzania during the dry and wet seasons of 2014, n=80.

Order	**Family**	**Species**	**Dry season Mean±SE**	**Wet season Mean±SE**
Hymenoptera	Braconidae	*Diaeretiella rapae*	0.093±0.138	0.086±0.032
Hymenoptera	Braconidae	*Aphidius colemani*	0.010±0.009	0.000±0.000
Coleoptera	Coccinellidae	*Hippodamia variegata*	0.010±0.007	0.002±0.001
Hymenoptera	Braconidae	*Aphidius colemani*	0.009±0.001	0.013±0.009
Coleoptera	Coccinellidae	*Scymnus pruinosus*	0.007±0.004	0.004±0.002
Coleoptera	Coccinellidae	*Cheilomenes aurora*	0.006±0.003	0.010±0.008
Hymenoptera	Eulophidae	*Formicid sp.*	0.004±0.003	0.008±0.004
Coleoptera	Coccinellidae	*Scymnus trepidulus*	0.004±0.002	0.003±0.002
Diptera	Cecidomyiidae	*Aphidoletes aphidimyza*	0.004±0.002	0.006±0.003
Coleoptera	Coccinellidae	*Cheilomenes sulphurea*	0.003±0.002	0.003±0.003
Coleoptera	Staphylinidae	*Paederus sabaeus*	0.003±0.002	0.002±0.001
Hymenoptera	Ichneumonidae	*Diadegma semiclausus*	0.002±0.002	0.003±0.002
Diptera	Syrphidae	*Syrphid sp.*	0.002±0.001	0.006±0.000
Hymenoptera	Braconidae	*Opius sp.*	0.002±0.001	0.000±0.000
Araneae	Lycosidae	*Lycosid sp.*	0.001±0.001	0.000±0.000
Coleoptera	Coccinellidae	*Brumoides fulviventris*	0.001±0.001	0.000±0.000
Coleoptera	Coccinellidae	*Scymnus kibonotensis*	0.001±0.001	0.001±0.001
Coleoptera	Coccinellidae	*Scymnus levaillanti*	0.001±0.001	0.000±0.000
Hymenoptera	Braconidae	*Apanteles sp.*	0.001±0.001	0.001±0.001
Hymenoptera	Eulophidae	*Dyglyphus sp.*	0.001±0.001	0.004±0.003
Mantodea	Mantidae	*Mantis sp.*	0.001±0.001	0.000±0.000
Mantodea	Mantidae	*Sphodromantis virids*	0.001±0.001	0.000±0.000
Neuroptera	Chrysopidae	*Chrysoperla carnea*	0.001±0.001	0.001±0.001
Coleoptera	Coccinellidae	*Scymnus sp.*	0.000±0.000	0.006±0.004
Coleoptera	Coccinellidae	*Micraspis sp.*	0.000±0.000	0.001±0.001

Order	Family	Species	Dry season Mean±SE	Wet season Mean±SE
Coleoptera	Staphylinidae	*Staphylinid sp.*	0.000±0.000	0.001±0.001
Hymenoptera	Eulophidae	*Eulophid sp.*	0.000±0.000	0.002±0.001
Hymenoptera	Eulophidae	*Crematogaster sp.*	0.000±0.000	0.001±0.001
Hymenoptera	Eulophidae	*Lasius sp.*	0.000±0.000	0.003±0.002
Mantodea	Mantidae	*Miomantis binotata*	0.000±0.000	0.001±0.001

4.4.5 Diversity of pests and natural enemies in Ethiopian kale

In this study, a total of 9316 individuals from 86 species, 42 families, and 12 orders were identified. The Renyi diversity profiles of low and mid-altitude zones of the dry and wet seasons touched each other indicating that there were no significant differences in species diversity. The dry season had higher species richness indicated by alpha=0 was 4.32 at mid than 4.1 in the low altitude regions. Species evenness in the low altitudes was 0.69 and 0.69 in the mid as indicated by alpha=Inf. The Simpson index was higher mid altitude zones in both seasons indicating a few species occurred in large numbers (Figure 4-3).

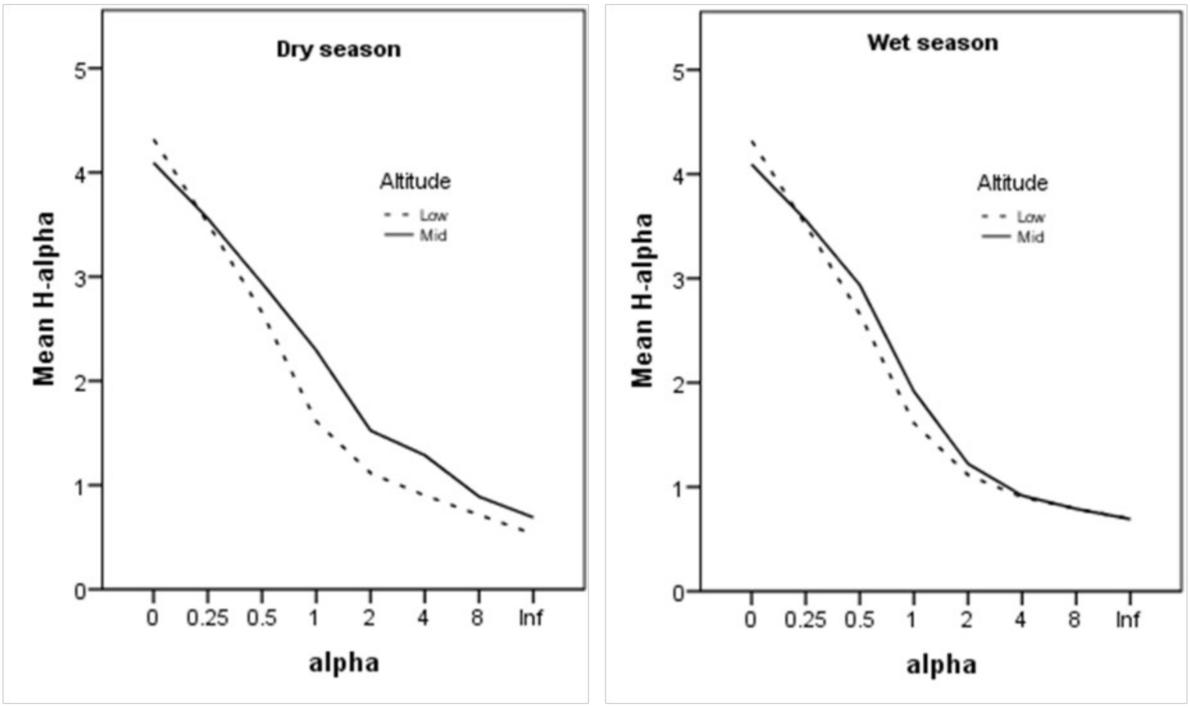

Figure 4-3: Renyi diversity profiles for Ethiopian kale pests and associated natural enemies in low and mid-altitude zones during the dry season (left graph) and wet season (right graph) of 2014 in eight regions of Tanzania, n=80.

4.4.6 Insect orders damaging Ethiopian kale.

There was a significant difference ($p<0.001$) in damage caused by the different pest orders in the dry season. Hemiptera caused the highest damage (30%) followed by Lepidoptera (25%), Hymenoptera (4.6%), Coleoptera (1.6%), Orthoptera (0.9%), Dipterans (0.6%) and Thysanoptera caused the least damage of 0.3%. Similarly, during the wet season, there was also a significant difference ($p<0.001$) in the damage caused by the pest orders. Hemiptera caused the highest damage (16.8%) followed by Lepidoptera (14.8%), Thysanoptera (3.7%), Orthoptera (2.3%), Coleoptera (1.5%), Hymenoptera (1.0%) and Diptera causing the least damage of 0.8% (Figure 4-4).

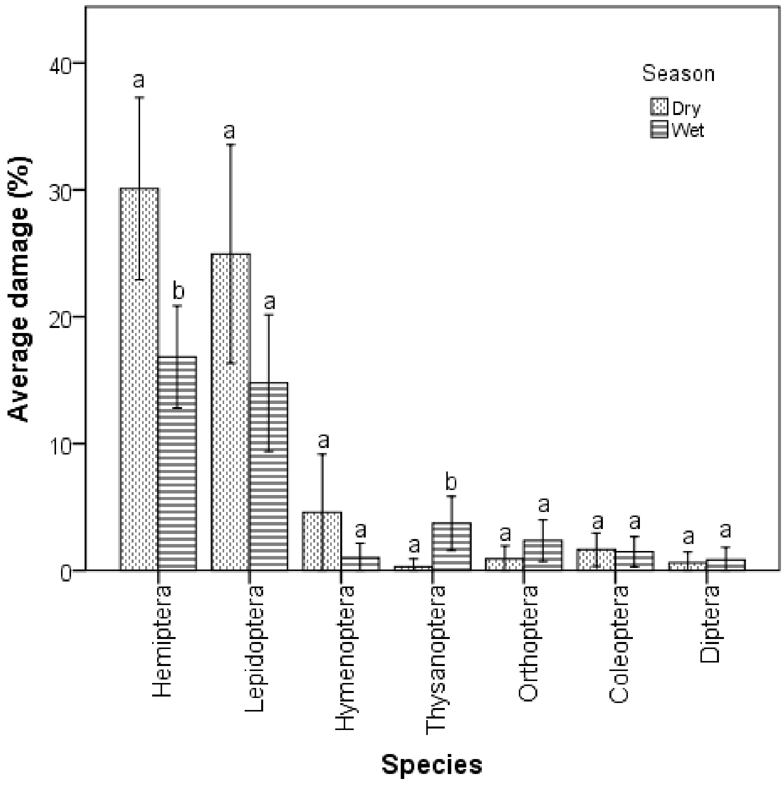

Figure 4-4: Average damage of pest orders of Ethiopian kale per farm in dry and wet season of the 2014 survey carried out in eight regions of Tanzania. (ANOVA; Means compared using Tukey test, p=0.05, n=80).

4.5 Discussion

The level of complexity in the interactions between several factors such as climate, seasons, topography, and cropping systems influence the presence of a species and thus diversity (Reddy, 2017). In our study, the species evenness index was low indicating that a few species were dominant in the fields. *B. brassicae* and *M. persicae*, aphid species were dominant across regions, altitudes, and seasons. The presence of certain species also depends on factors such as the earlier establishment of its host. This is evident in this study as *D. rapae* an aphid parasitoid was the most abundant natural enemy species corresponding to the high abundance of aphids.

The ranking of Diamondback moth as a major pest in this study also confirms other reviewed reports citing the species as a major problem in brassicas (Loehr et al. 2004). Also, the use of broad-spectrum pesticides such as Abamectin, Diazinon, lambda-cyhalothrin that farmers reported during the survey as some of the pesticides used for pest control is known to suppress populations of beneficial insect (Fernandes et al., 2010). However, diamondback moth was more abundant in the mid altitude regions such as Mbeya, Dodoma, and Arusha which are also major producing regions of brassicas such as cabbage that are the main hosts of the pest.

D. rapae, a cosmopolitan aphid parasitoid was the most abundant natural enemy corresponding to the high abundance of its hosts, *B. brassicae* and *M. persicae* aphids observed during this study. *A. colemani* was the second most abundant natural probably because it is a parasitoid of two of the aphid species observed i.e. *A. gossypii* and *M. persicae* but not *B. brassicae*. Pollen and nectar are considered critical for the fitness and abundance of adult braconid wasps, lace-wings, and hoverflies (van Rijn & Wäckers, 2016) which were among the main groups of natural enemies observed during the survey. Therefore, the high abundance of natural enemies in the mid-altitude of the dry season and the low altitude in the wet season may be due to the presence of rains in these areas that supported a variety of flowering plants.

In this study, we found the highest damage in the low altitude areas in the dry season. There were old Ethiopian kale crops observed in the dry season which harboured more pests known to damage older Brassica crops. These include bagrada bugs whose feeding results in large stippled areas that eventually wilt and die leaving a leaf scotch appearance (Reed et al., 2014). Hemipterans mainly sap-sucking aphids and Lepidopterans that defoliated the leaves were the most damaging pests of Ethiopian kale in this study. This confirms observations made by stakeholders in *B. carinata* production and marketing in Tanzania that leaf defoliators and aphids together with their associated diseases were the major constrain in the production of the vegetable (Adeniji & Aloyce 2014). Additionally, this species identification work will assist to prioritize pest species according to their importance in the production of Ethiopian kale.

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5 Plant Nutrition Impacts Host Selection in Red Spider Mites: A Mini-Review (based on Mworia *et. al*. 2017)

5.1 Abstract

Plants are continuously challenged by pests and diseases both in greenhouses and in the open fields. The continuous exposure has led to plants developing a number of defence mechanisms against attacking herbivores that are largely characterized by antixenosis, antibiosis, and tolerance. On the other hand, herbivores have evolved and developed complex strategies to overcome plant defences and successfully locate, feed and reproduce on plants. The complexity of herbivore-plant interactions has led to various studies seeking to reveal the main components of these relationships. The results of such studies involving various herbivorous mites are discussed herein. Although they point to plant nutrition as a key factor in these interactions, the results vary largely, suggesting that each interaction is plant-herbivore specific under prevailing conditions. This review, therefore, aims at highlighting the influence of plant nutrition on plant-mite interactions while focusing on the possibility of regulating plant nutrition as a tool for integrated pest management. The influence of external factors as determined by fertilizer and water regimes are also discussed.

Key words: plant-mite interactions, host quality, secondary metabolites

5.2 Introduction

The process of host choice in arthropods is a complex phenomenon that involves a series of activities that include selection, acceptance, and suitability of the host plant (West & Cunningham 2002). In host selection, the initiation stage includes host location where pests use volatile plant compounds as cues for host plant identification (Bruce *et al*.,2005). Host acceptance is characterized by brief probing into the leaf tissues to assess the nutritional value and secondary metabolite composition and when the host is suitable, then prolonged ingestion follows (Powell et al., 2006). A plant is suitable as a host if it meets the dietary requirements of the pest and offers offspring development (West & Cunningham 2002).

Host selection in arthropods is described in a number of models which include hierarchy-threshold, preference hierarchies or preference-performance (Cunningham & West, 2008). In hierarchy-threshold models, the selection of a host plant by a herbivorous arthropod depends on the positive stimuli received by the pest from the plant (Courtney et al., 1989). In this case, the acceptance or rejection of the host plant is purely determined by herbivore behaviour. In preference hierarchies, herbivores make a choice from the available species according to their preference and only opt for the least preferred when the more preferred species are absent, i.e. decision based on experience made in the habitat (Courtney 1989; West & Cunningham 2002). Preference-performance hypothesis postulates that females prefer host plants that offer their offspring best fitness and ensure survival (*Gripenberg* et al., 2010a). Some pests have specific minimal carbon and nitrogen requirements that must be acquired from the host for sustained reproduction whereas, for others, reproduction is triggered by nutrient depletion (Analytic, 2008). These activities are all determined by various factors, key among them being the host nutritional value that depends on the environment within which the host grows (West & Cunningham 2002).

5.3 Components of host nutritional value for mite pests

The nutrition of a host plant is vital in meeting the dietary requirements of herbivorous mites (Wermelinger et al., 1991). Mites feed by inserting their stylet 70-120 µm into the leaf surface, piercing the mesophyll cells where they inject saliva and then suck out the cytoplasm of the cells (Tomczyk & Kropczynska, 1985). Since their feeding induces defence response in the host plant, their saliva usually contains proteins that reduce the adverse effects of the plant defences (Villarroel et al., 2016). Egg laying females are known to cause the greatest damage to plants due to their increased energy demand during the oviposition period (Boudreaux, 1958). Leaf nitrogen, water, and secondary metabolites are considered as the major constituents of leaf tissue that determine a host nutritional value to herbivores and all depend on the availability of plant nutrients (Eigenbrode & Pimentel, 1988).

Nitrogen (N) in form of proteins and amino acids is required by arthropods for growth and development. With 8-10% dry weight of herbivores being nitrogen against 0.03-7% in plants, herbivorous pests like mites have to take up large amounts of food to obtain adequate nitrogen (Mattson, 1980). Nitrogen is observed to influence population density, fecundity, oviposition, development time and survival of mites (Geddes 2010; Chow . 2009). This can be attributed to the fact that when N is relatively more than the other macronutrients, plants become more succulent because carbohydrates are utilized for protein synthesis rather than cell walls (Mellors & Propts, 1983). Also, plants suffering nitrogen (N), phosphorus (P) and potassium (K) deficiency are known to accumulate soluble nitrogen compounds and thus become more susceptible to sucking herbivores (Ashilenje . 2011; White 1984). In addition, because leaf nitrogen increases with the nitrogen available to a plant, high N application leads to more N inform of free amino acids and reduced concentrations of secondary metabolites which provides the perfect environment for increased population growth of herbivores (Herms, 2002).

Leaf water content is considered to influence food utilization in arthropods (Mattson, 1980) just as soil moisture influences total nutrient availability and effective nutrient balance. This is because nitrate ions are known to move by mass flow to the roots and are much more mobile in the soil than phosphate and potassium ions which move to the roots by diffusion (Mellors & Propts, 1983). Consequently, soil moisture has been associated with mite feeding. For example, low soil moisture has been reported to promote the reproduction of *Tetranychus urticae* Koch (Acari, Tetranychidae) in strawberry (White & Liburd, 2005). In addition, drought-stressed tomatoes were found to suffer high leaf damage caused by *Tetranychus evansi* Baker & Pritchard which was attributed to increased free sugars, amino acids i.e. proline which stimulated feeding and egg laying (Ximénez-Embún et al., 2016). In the case of bush beans where the plants were subjected to four levels of water supply, the population of *T. urticae* was highest in the well watered and severely drought stressed plants (English-Loeb, 1990) highlighting the importance of establishing optimal irrigation regimes for spider mite management. These observations are due to an increase in soluble nitrogen and free amino acids, carbon-based and nitrogen-based secondary metabolites and leaf temperature that are typical in drought-stressed plants (Herms, 2002). Also, it is known that during water stress, leaves retain more water and this reduces the humidity around the leaves. As a result, mites increase their feeding to prevent dehydration but also excrete less water and therefore more energy is available for reproduction (Boudreaux, 1958).

Normally, plants cannot simultaneously allocate resources to growth and defense (Toor, 2006). Therefore, although high concentrations of secondary metabolites can result in a more resistant plant against pests, their production is usually costly and reduces plant growth and development (Mazid, TA2, & Mohammad F, 2011). Evidence of such trade-offs has been reported in a number of crops including *Senecio jacobea* in which plants with high concentrations of pyrollizidine alkaloid grew slower that those with low concentration when grown under limited light, nitrogen, and phosphorus (Vrieling & Vanwijk, 1994). Also in Asteraceae plants whose growth was most restricted contained most toxic tissues (Almeida-Cortez *et al*., 2004) Another example of costs and benefits of secondary metabolites is that of *Cecropia Peltata*, a neotropical tree where plants with high Tannin concentration experienced low leaf damage but also low leaf production (Coley, 1986). A number of secondary metabolites have been associated with plant defence against red spider mites by acting either as toxins, repellents, digestibility reducers, oviposition deterrents or promoting the effectiveness of natural enemies of mites (Dicke & Sabelis, 1988). These secondary plant compounds include alkaloids, phenols, and terpenoids among others.

Alkaloids are an important group of plant metabolites involved in defence against herbivorous pests in solanaceous plants (Chowański et al., 2016). Water and soil fertility are considered as factors that influence alkaloid production. Brown & Molyneux (1996) reported that water and nutrient deficiencies reduced the total alkaloids by 50% in groundsel, *Senecio vulgaris* L. whereas the deficiency of water or nutrient alone did not significantly reduce the alkaloids. The total alkaloid content of datura, *Datura innoxia* Mill was also reported to increase with increasing levels of compound fertilizers (Al-Humaid, 2003). In potatoes tubers, high rates of nitrogen fertilizer are known to increase the concentration of glycoalkaloids (Love et al., 1994). Total alkaloid, vincristine and vinblastine content in periwinkle, *Catharanthus roseus* L seedlings were also reported to accumulate with increased water stress (Amirjani, 2013). Similarly, the maximum total alkaloids in black henbane, *Hyoscyamus niger* L were realised in plants grown under severe and moderate water deficit stress combined with high nitrogen supply (Ghorbanpour, 2014). However, in some plant species, the plant's alkaloid content is greatly dependent on its genetics i.e. species. For example in African nightshades (Solanaceae), steroidal glycoalkaloids were present in the mite resistant *Solanum sarrachoides* compared to the mite susceptible species *S. villosum* Miller and *S. scabrum* Miller (Jared et al., 2016).

Phenols are chemical compounds involved in the development of plant resistance against various herbivores through causing mortality, repellence and deterring oviposition (Chen & Dai, 2015). Red spider mites induce defence reactions in their host plants and an example in cucumber, *T. urticae* increased the total phenols six days after feeding on the plant (Tomcizyk , 1992). The induced phenols act on the pest causing adverse effects like reducing its fitness. For example phenols from strawberry have been reported to increase repellence and mortality while reducing ingestion and fecundity of *T. urticae* (Dabrowski & Bielak, 1978). In the same plant, foliar catechol phenols known to bind to digestive enzymes and inactivate them, are associated with delayed developmental times of *T. urticae* (Luczynski, 1990). Similarly, in peppermint, increase in total phenols reduced the number of eggs laid, increased dispersal and development time of *T. urticae* (Larson & Berry, 1984). Toxic, repellent and oviposition-deterrence activities have also been observed on *Tetranychus cannibarinus* Boisduval from 2,4-di-*tert*-butylphenol (Yijuan Chen & Dai, 2015).

Terpenoids are highly volatile compounds that contribute to the aromatic properties of the plants that produce them and are used by the plant for its protection against herbivore damage either as toxins or attractants of natural enemies of their pests (Chowański *et al*., 2016). In lima beans, (E)-β-ocimene and (3E)-4,8-dimethyl-1,3,7-nonatriene are terpenoids that are considered as predator attractants induced by the feeding of *T. urticae* (Dicke & Sabelis, 2000). Terpenoids such as gossypol found in cotton have been associated with reduced damage by *T. urticae* on cotton lines with high gossypol content (Schuster *et al*,1972).

5.4 Impact of plant nutrition on herbivorous mites

Optimum plant nutrition offers protection against pest attack and conversely, the deficiency or excess of certain minerals may predispose plants to pest damage (Ashilenje *et al*., 2012). For example, plants suffering nitrogen, phosphorus and potassium deficiency accumulate soluble nitrogen compounds and thus become more susceptible to sucking herbivores (Ashilenje . 2011; White 1984). In a similar way, high nitrogen application leads to more free amino acids and reduced concentrations of plant secondary metabolites, a perfect recipe for increased population growth of herbivores (Herms, 2002). Table 5-1 lists a number of studies that have focused on the influence of plant nutrition on the development and population dynamics of spider mites on apple trees, cotton and maize among others (Yan Chen et al., 2007; Chow et al., 2009; Geddes, 2010; Wermelinger et al., 1991).

A study by Wermelinger *et al.* 1991 on the effects of four levels of the macronutrients, N, P and K on *T. urticae* on micro propagated apple trees confirmed that leaf nutrient concentrations correspond to respective treatments but phenolic compounds in the leaves increased with N and P deficiency. For mites, preimaginal developmental rate and oviposition rates were reported to positively correlate with leaf N while fecundity often correlated positively to N and carbohydrates contents of the leaves but negatively to the phenolic content. In cut roses, red spider mites are a pest of economic importance as they directly affect the quality of the cut-flower. A study by Chow (2009) are among attempts that have been made to use cultural practices like altering the fertilization levels of N to control *T. urticae*. The authors reported that eggs and mites per flower shoot on rose plants supplied with 100% of the recommended N level were double relative to those fertilized with 33% and 50%. Further, the fertilizer treatments did not affect the number of total shoots produced but influenced flowering and blind shoots. Those plants receiving 33% had significantly more blind shoots than those of 100% N.

Another study by Chen (2007) reported that geraniums treated with different P rates had more *T. urticae* populations eight weeks after application but the plant quality and dry matter remained high, implying that these plants better compensate for mite feeding damage. In addition, the study by Chen (2007) suggested that tissue nutrient content might have influenced the selection of feeding sites by mites since there was a positive correlation between the within-plant distribution of mites and tissue nutrient concentrations.

Table 5-1: Direct and indirect effects of different host plant treatments with fertilizer on the performance of herbivorous mites.

Nutrient factor	Host plant	Host type	Mite species	Effect on mites	Reference
Population density					
N	Apple trees	Perennial	*Panonychus ulmi*	Increased with high N	(Van de Vrie & Delver 1979)
N,P,K	Apple trees		*P. ulmi*	Higher with highest and lowest NPK	(Sharma . 2010)
N	Apple trees		*T. urticae*	Increased with high leaf N	(Wermelinger . 1991)
P	Apple trees		*T. urticae*	Higher with P-deficiency	(Fritzsche et al, 1980)
N	Pecan		*Eotetranychus hicoriae*	Higher with N fertilization	(Jackson & Hunter, 1983)
N	Ivy geranium		*T. urticae*	No difference in N rates	(Yan Chen et al., 2007)
P	Ivy geranium		*T. urticae*	Higher with high P rates	(Yan Chen et al., 2007)
N	Sorghum	Annual	*Oligonychus pratensis*	No relationship	(Perring et al., 1983)
P	Sorghum/corn		*O. pratensis*	Slight influence	(Archeret al, 1988)
N	Cucurbits		*T. neocaledonicus*	Higher populations	(Sharma & Pande 1986)
K	Cucurbits		*T. neocaledonicus*	Higher populations	(Sharma & Pande 1986)
N,P,K,S	Cowpea		*T. turkestani*	Higher with N,P,K,S fertilization	(Rather & Lavdari 2006)
N	Brinjal		*T. macfarlanei*	Higher with high N	(Patil & Nandihalli 2008)
N	Common bean		*T. urticae*	Higher with high N	(Saeid et al., 2011)
N	Jute		*Polyphagotarsonemus latus*	Higher with high N	(Gotyal . 2016)
Fecundity					
N,P,K	Lima beans	Annual	*T. telarius*	More progeny with higher N,P,K	(Henneberry, 1962)
Oviposition					
N	Roses	Perennial	*T. urticae*	More with increasing N	(Chow . 2009)
N	Apple trees		*T. urticae*	Increased with increase in leaf N	(Wermelinger . 1991)
K	Grapes		*Eotetranychus willametei*	Higher density with increased K	(Geddes, 2010)
Survival					
N	Grapes	Perennial	*E. willametei*	Better on moderate than high N	(Geddes, 2010)
P	Beans	Annual	*P. ulmi*	Higher survival	(Suski and Badowska 1975)
K	Beans		*T. urticae*	Higher mortality	(Suski and Badowska 1975)

Results are structured according to effects on mite density, fecundity, oviposition, survival, maturity, and longevity of the different mite species on treated host plants (annuals and perennials). N=nitrogen, P=phosphate and K=potassium

Life history parameters of several mite species indicate how plant-mite interactions are influenced by the supply of fertilizers and possible outcomes in future work with other plants species (Table 5-1). These studies are particularly important in guiding research of less developed crops such as African leafy vegetables most of which are damaged by different spider mite species. These vegetables include Amaranth that is damaged by *T. urticae*, vegetable cowpea attacked by carmine spider mite, *Tetranychus cinnabarinus* Boisduval (Acari: Tetranychidae), green spider mite, *Tetranychus arabicus* Attiah (Acari: Tetranychidae) (Oyewale & Bamaiyi, 2013), Ethiopian kale that hosts *T. urticae*, red legged earth mite, *Halotydeus destructor* Tucker (Acari:Penthaleidae) and blue oat mite *Penthaleus sp.* Koch (Acari: Panthaleidae*)* (Mcdougall et al., 2014), cucurbit leaves damaged by bean spider mite, *Tetranychus ludeni* Zacher*, H. destructor*, broad mite, *Polyphagotarsonemus latus* Banks (Acari:Tarsonemidae), blue oat mite, *Penthaleus major* Duges and clover mite, *Bryobia cristata* Duges (Acari: Postigmata)(Napier, 2009), jute plant that is fed on by *P. latus* and *Oligonychus coffeae* Nietner (Acari: Tetranychidae (Sadat & Chakraborty, 2015) and edible nightshades that are differentially attacked by *Tetranychus species* (Murungi et al. 2014). This mini-review will focus on African nightshade which is as an economically and nutritionally important leafy vegetable in African communities.

5.5 African nightshade

African nightshade (*Solanum* sp.) is an important leafy vegetable in East Africa. In Kenya, the vegetable accounts for 29% of the domestic value of African leafy vegetables (HCDA, 2012) and 35% market share of total indigenous vegetables in urban markets and supermarkets within Nairobi (Irungu *et al.*, 2007). Its demand has been on the rise especially among urban dwellers due to increased awareness of its nutritional and medicinal value (Irungu et al., 2007). African nightshades thrive in soils rich in N, P and organic matter

(Ojiewo, 2013). Applications of 2.5-5 g N plant^{-1}, 40-52 Kg N ha^{-1}, 6 kg M$^{2-1}$ of cattle manure or 8 tha^{-1} fortified compost manure are recommended for the crop (Ondieki et al. 2011; Ashilenje et al. 2011 and Abukutsa-Onyango & Karimi 2005). However, the growing demand for the vegetable has not been met owing to a number of constrains in the value chain. Among these are production constrains such as pest damage (Irungu et al., 2007). African nightshades are damaged by arthropod pests such as aphids (Ashilenje et al., 2012), beetles (Boavida & Germain, 2009), leaf miners (Foba et al, 2015), leafhoppers, grasshoppers, lepidopterans (Clarke, 2005), mealybugs, nematodes (Nchore, 2013), whiteflies (Caspi-Fluger et al., 2012) and red spider mites (Fiaboe, 2007). A recent field monitoring in Tanzania and Kenya underlined the general importance of the red spider mites as key pests of nightshades (Mureithi, 2015).

5.6 Status of Tetranychus evansi

Tetranychus evansi, the tomato spider mite has become a serious invasive pest of solanaceous crops in Africa though it is also known to damage more than 30 other plant families (Navajas *et al*., 2013). From its area of origin in Brazil, where it was initially observed in 1952, it has successfully invaded various countries across the world due to its ability to survive in a wide range of temperatures (10-34°C) (Furtado et al., 2007), high reproductive rate (200eggs per female) at short generational time (13.5 days at 25°C) and high dispersal ability (Bonato, 1999). Also, the mite is able to suppress the induction of salicylic and jasmonic acid signalling routes that are involved with induced defence of the host (Sarmento et al., 2011). These has been demonstrated in experiments where *T. evansi* was shown to have a higher oviposition and adult survival on plants that were previously damaged by *T. evansi* due to reduced inducible defence compounds. The suppressed defence is partly due to effector-like salivary proteins that are secreted by mites to reduce the adverse effects of plant defence (Villarroel et al., 2016).

Although tomato red spider mite is closely related to *T. urticae* it has been shown to be more aggressive and difficult to control. Only recently has a predatory mite, *Phytoseiulus longipes* been shown to successfully control *T. evansi* (Furtado *et al*., 2007) (Silva et al., 2010) while *T. urticae* was effectively controlled using predatory mites, *Phytoseiulus persimilis* Athias-Henriot and *Neoseilus californicus* McGregor that are commercially available. The two predatory mites have not been successful in controlling *T. evansi* due to reduced population growth when fed on *T. evansi* (Escudero & Ferragut, 2005). This occurrence is thought to result from toxic and antifeedant effects of secondary plant metabolites found in solanaceaous plants that *T. evansi* feeds on. Examples of such metabolites are methyl ketones (Chatzivasileiadis & Sabelis, 1997), sesquiterpenes (Maluf et al., 2001) and glycoalkaloids (Jared et al., 2016).

Fertilizer and water application are among cultural practices that can be explored in the management of *T. evansi*. Studies into the impact of either complete nutrient recipes or individual nutrient rates could reveal levels that can be useful in keeping mite damage at a minimum while supporting high productivity. Preliminary results are promising, showing that red spider mites prefer and develop best on well-nourished plants i.e. plants grown on 80% water field capacity and complete nutrient solution (Mworia, 2015). In addition, since fertilizers and water supply to plants are known to impact on the secondary metabolites that are involved in plant-pest interactions, it is worth investigating how major metabolites in African nightshades are influenced. Consequently, relationships can be established between metabolites and mite incidences in an attempt to identify those that can be manipulated for mite management.

5.7 Conclusion

In general nitrogen application leads to elevated leaf N content that positively influences most life-history parameters of red spider mites. However, the ratio of N compared to other macro and micronutrients has shown varying effects. Therefore, host plant quality that depends on plant nutrition influence the choice and performance of mites. In this regard, there is need to study complete fertilizer and water regimes and establish their effects on the plant metabolites influencing the performance of spider mites. The results of which will point to possible optimal nutritional requirements of these vegetables that will lead to high plant defence against mites while maintaining acceptable yield levels. In so doing, fertilizer and water regimes could be used as an effective tool in an integrated pest management system of red spider mites in African leafy vegetables leading to higher yields, improved nutrition, and food secure communities.

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6 Effects of fertilizer and water regimes on host selection of *Tetranychus evansi* (Tetrachynidae) on *Solanum scabrum*

6.1 Abstract

Host plant quality impacts various developmental stages in arthropods and affects the population build up. In this study, the effects of fertilizer and water regimes on host selection of *Tetranychus evansi* Baker and Parker were studied using greenhouse experiments and leaf discs assays. Three varieties of *Solanum scabrum* varieties were treated with nine fertilizer and water regimes. Leaf discs were obtained from leaves in each regime and then female *T. evansi* mite was placed on each leaf disc. The number eggs laid after 24, 48 and 72 hours were then counted. Fertilizer and water regimes did not affect the number of eggs laid on the leaf discs (p=0.35). Among the three varieties, more eggs were laid on Abuku2 variety, double the number laid on leaf discs of Abuku1 and Olevolosi varieties.

Key words: Plant nutrition, pest management, cultural practices, host susceptibility

6.2 Introduction

Host plant selection in arthropods is crucial for their survival and consequently of importance in pest management. Host plant quality is an important aspect of host selection and involves morphological, physiological, and biochemical traits of a plant most of which are influenced by plant nutrition (Louda & Collinge, 1992). Application of water and fertilizers are key agronomic practices in crop production that supplement plant nutrients. As a result, aspects of leaf quality that are of significance to herbivorous insects such as leaf nitrogen, water content, and secondary metabolites all depend on the availability of plant nutrients (Eigenbrode & Pimentel, 1988). Arthropods can detect stimulatory compounds that signal suitability or deterrent compounds that caution of the unsuitability of a plant (Renwick & Lopez, 1999). In the presence of sufficient stimulation from a plant, females lay eggs on the plant indicating host plant acceptance (Tosh et al. 2003; Yano et al. 1998).

The African nightshade, *Solanum scabrum* is a green leafy vegetable of African origin that is widely used in East Africa. The leaves are rich sources of vitamins A, B and C, proteins, mineral such as Iron, Calcium, Iodine, Phosphorus, and Zinc and also contains phenols and alkaloids such as nicotine, quinine, cocaine, and morphine known for their medical properties (Ochieng et al., 2007). African nightshade is attacked by several pests such as aphids, leaf miners, whiteflies, grasshopper, and red spider mite.

Tetranychus evansi, also known as the tomato red spider mite is a destructive pest of African nightshade and other solanaceous crops in Africa (Boubou, 2011). Pesticides have commonly been used as a way of managing mites but mites have since developed resistance to most pesticides making its populations build up during the production season after natural enemies are eliminated by the pesticides (Bagarama, 2014; Navajas et al., 2013).

Therefore, because of the importance of arthropod host selection stage in pest management, the role of plant nutrition in host selection and the need for simple and sustainable pest management strategies by small scale growers of Africa indigenous vegetables, this study seeks to answer the question, how do fertilizer and water regimes affect host selection of *T. evansi* on *Solanum Scabrum*?

6.3 Methodology

6.3.1 Plant materials

Seeds of *S. scabrum* variety Olevolosi were obtained from the World Vegetable Centre (AVRDC, Arusha, Tanzania), while those of *S. scabrum* varieties Abuku1 and Abuku2 were obtained from Professor Mary Abukutsa of Jomo Kenyatta University of Agriculture and Technology.

6.3.2 Plant culture

Plants were raised in greenhouse benches by planting 8-10 seeds in 3 kg plastic pots containing 2:1 mixture of sterilized river sand and red soil. In the third week when most of the seeds had germinated thinning was done to retain a single plant per pot and watered daily depending on the ambient climatic conditions. Fertilizer treatments and water treatments were applied once per week from the 3rd week and water supplied as 40, 60 and 80% field capacity by measuring the soil moisture using a Time Domain Reflectometer (TDR) from Soilmoisture Corporation in Califonia.

6.3.3 Treatments

Three fertilizer treatments were applied as different dilutions; full strength (1) as the control, half strength (0.5) and quarter strength (0.25) of the Hoagland's nutrient solution. The solution was prepared by first making stock solutions from macro and micro nutrients from which a working solution was then made as described by (Hoagland & Arnon, 1950). The stock solution with Macronutrients was made from 202g/L of KNO_3, 493g/L $MgSO_4.7H_2O$, 136g/L KH_2PO_4, 236g/L $Ca(NO_3)_2.4H_2O$ and 80g/L NH_4NO_3 salts. For micronutrients stock solution, 1.81g/L $MnCl_2.4H_2O$, 0.0051g/L $CuSO_4$, 0.22g/L $ZnSO_4.7H_2O$, 0.12g/L $Na_2 MoO_4 \times 2H_2O$, 2.86g/L H_3BO_3 and 15g/L $FeSO_4.7H_2O$ salts were used. Three water regimes i.e. 40%, 60 %, and 80% field capacity were used. Soil moisture levels were measured using a Time Domain Reflectometer (TDR) (Soil moisture Corporation California, USA). Three water treatments were also applied. These were 40, 60 and 80% field capacity.

6.3.4 Counting of eggs

A single leaf disc of 15mm in diameter from the 9 fertilizer and water treatment combinations for each of the three lines was placed on wet cotton wool on a petri-dish and a single female mite introduced on the leaf disk. This was repeated 3 times with petri-dishes placed in an incubator set at $25 \pm 3^{\circ}$ C in temperature and 70-80% relative humidity. After 24, 48 and 72 the number of eggs on each leaf disk was counted under a dissecting microscope.

6.3.5 Statistical analysis

The expected number of eggs laid between treatment, time points, and varieties were analyzed using Bayesian statistics in the arm package in R software. Means were separated using the Tukey method.

6.4 Results

6.4.1 Effects of variety on oviposition of *T. evansi* on *S. scabrum*

There was a significant difference in the number of eggs laid over the three-time points ($F_{(2, 81)}$ =40.61, $p<0.001$). There were significantly more eggs laid at after on the 72nd hour than at 48th hour (Z=5.02) and 24th hour (Z=4.73). Also, the number of eggs laid on the 48th hour was more than in 24th hour, Z=2.54 (Figure 6-1).

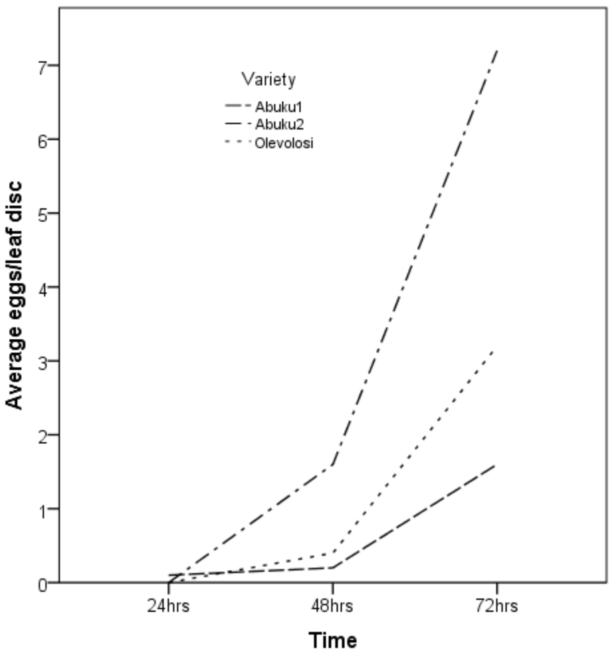

Figure 6-2. Mean of T. evansi eggs on leaf disc of African nightshade varieties, Abuku1, Abuku2 and Olevolosi at 24th, 48th and 72nd hours after introducing the female mite. N=3

The number of eggs laid were different between varieties ($F_{2, 81}$=13.30, p<0.001). Eggs laid on Abuku2 variety were significantly more than Abuku1 (Z= 4.13, p<0.001) but not Olevolosi (Z=2.38, p=0.16). Also, eggs laid on Abuku1 were not significantly different from those of Olevolosi, (Z=1.84, p=0.46).

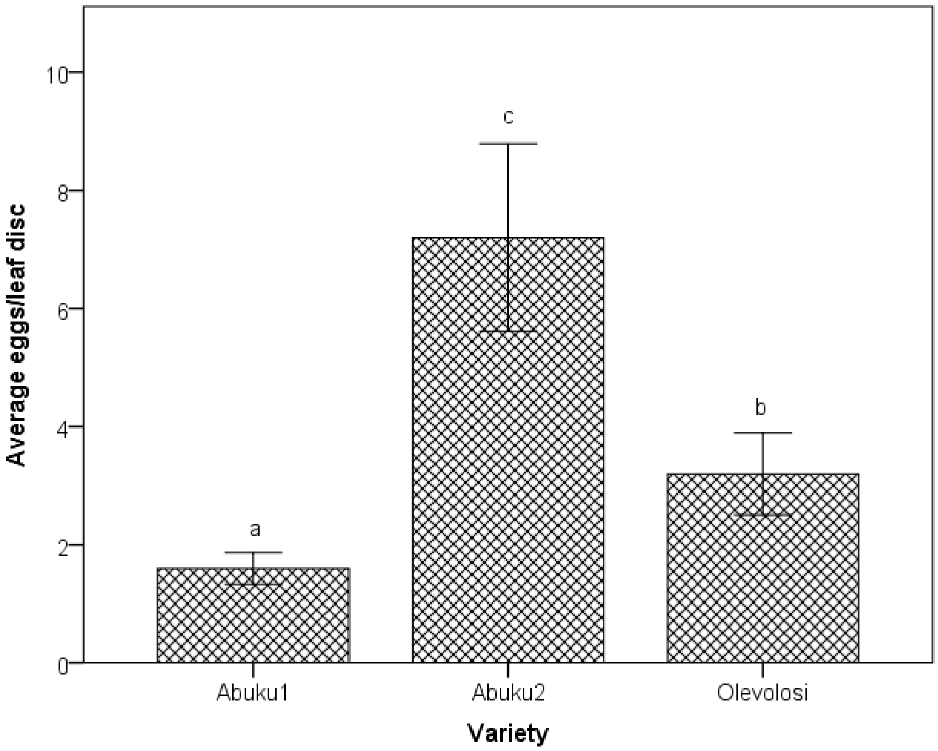

Figure 6-3. Mean number of *T. evansi* eggs on leaf discs of African nightshade varieties, Abuku1, Abuku2, and Olevolosi at the 72nd hour after introducing a female mite, ANOVA; Means compared using Tukey test, p=0.05, n=30)

6.4.2 Effects of fertilizer and water regimes on *T. evansi* oviposition

There were no significant differences in eggs between the nine fertilizer and water regimes ($F_{(8, 81)}$ =1.13, p=0.35). However, in general, leaf discs from plants grown under regimes with 80% water had more eggs. The least eggs were observed on leaf discs from plants grown under moderate nutrition i.e. 60%water and 0.5fertilizer regime (Figure 6-3).

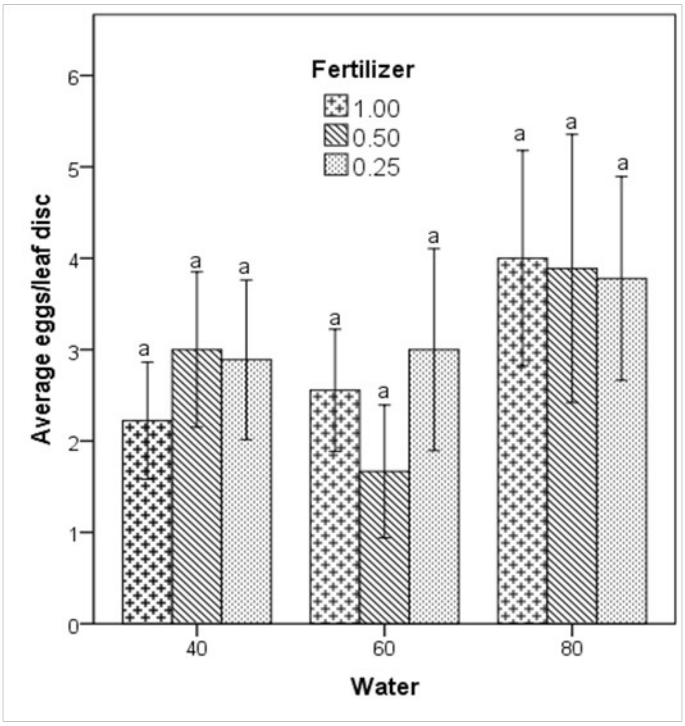

Figure 6-4. Mean number of eggs laid on *S. scabrum* leaf discs treated with 40, 60 and 80% water field capacity and fertilizer levels; 1, 0.5 and 0.25 concentration of Hougland nutrient solution 72hours after introducing a female mite. (ANOVA; Means compared using Tukey test, p=0.05, n=3)

6.5 Discussion

Fertilizer and water supply are important agronomic practices in crop production that have a profound impact on plant quality and may influence host selection by herbivorous arthropods (Tuwei et al., 2013; Altieri & Nicholls, 2003). According to the preference–performance hypothesis females are expected to oviposit on host plants on which their offspring have optimal fitness (Gripenberg, 2010b). Oviposition in arthropods such as aphids (Tosh et al., 2003) and mites (Yano et al., 1998) is an indication of host acceptance. Awmack & Leather 2002 in their review of host plant quality and fecundity in herbivorous insects indicates that host plant quality affects both potential and achieved herbivore fecundity.

In this study, oviposition was not significantly different in the different fertilizer and water regimes which are expected to vary host quality. These results concur with findings of (Underwood, 1994) that showed oviposition in *Eucheira socialis* (Pieridae: Lepidoptera) was not based on host quality. Therefore other factors may be involved in level oviposition in the mite. However, varietal differences were important factors influencing oviposition of the tomato red spider mites. This agrees with the finding of (Alagarmalai et al., 2009) in which the preference of free-moving broad mite, *Polyphagotarsonemus latus* was dependent on each species. Also, the fact that oviposition was significantly affected by variety, may emphasis the role of morphological, physiological and biochemical traits of a plant. Therefore, the choice of African nightshade varieties that deter oviposition by tomato red spider mite can a preventative measure in reducing mite infestations and subsequently improving yields and incomes of nightshade growers.

6.6 References

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7 Effect of fertilizer and water regimes on *Tetranychus evansi* (Tetrachynidae) population, leaf damage and leaf alkaloid content in *Solanum scabrum*

7.1 Abstract

Plant nutrition plays an important role in plant growth and defense against arthropod pests. In African nightshade (*Solanum* sp.) known to contain alkaloids, the tomato red spider mite, *Tetranychus evansi* Baker and Parker causes severe leaf damage. A greenhouse experiment was conducted to investigate the effects of fertilizer and water regimes on the *T. evansi* population and leaf damage over seven weeks and establish their relationship with leaf alkaloid content. Mite population and leaf damage increased with a decrease in soil moisture and nutrient concentration with 35% leaf damage in the highest regime to 73% in the lowest regime. Alkaloid content had a significant negative correlation to the mite population and leaf damage at extreme regimes. Therefore, irrigation and fertilization regimes potentially influence the severity of the damage associated with *T. evansi* in African Nightshades.

Key words: Plant mites, nutrition, plant defense, crop protection

7.2 Introduction

African nightshades (Solanales, Solanaceae) are used as leafy vegetables in East African communities (Schippers, 2002). The leaves are rich sources of nutrients and phytochemicals (Sivakumar et al., 2018). Alkaloids are one of the chemical compounds found in African nightshades and known for their medicinal properties (Chowański et al., 2016). However, African nightshades are damaged by pests such as aphids, beetles, leaf miners and red spider mites posing a major challenge to growers (Mureithi et al., 2017).

The tomato red spider mite, *Tetranychus evansi* Baker and Pritchard is a destructive pest of the Africa nightshades, especially during dry and hot conditions. Steroidal glycoalkaloids such α-solasonine, α-solamargine, tomatine and demissine found in African nightshades have been associated with host plant resistance to *T. evansi*, (Jared et al., 2016). Soil moisture influences the nutrient availability and nutrient balance within a plant and is known to affect herbivore behavior. In bush beans, when plants were subjected to four levels of water supply, the population of *T. urticae* significantly increased in well-watered and severely drought-stressed plants and lowest in the moderate drought-stressed plants (English-Loeb, 1990). These observations were thought to be due to increases in soluble nitrogen and free amino acids, carbon-based and nitrogen-based secondary metabolites and leaf temperature that are typical in drought-stressed plants.

Plant nutrients also influence the synthesis of alkaloids. For instance, hyoscyamine content in henbane plants, *Hyoscyamus niger* is known to increase with increasing nitrogen and calcium concentrations (Alaghemand et al, 2013). Also, the total alkaloid content of *Datura innoxia* has been shown to increase with increasing levels of compound fertilizers with the peak being attained with 600kg ha^{-1} (Al-Humaid, 2003). Additionally, the maximum total alkaloids in

Hyoscyamus niger were realized in plants grown under severe and moderate water deficit stress combined with high nitrogen supply (Ghorbanpour, 2014).

The control of *T. evansi* in African nightshades has been largely through the use of pesticides although mites have developed resistance to the commonly used acaricides. In this respect, the use of effective nutrition management as a strategy to reduce pests damage has not been exploited (West & Nansen, 2014). The current study, therefore, aims to determine the effects of different regimes of fertilizer and water on the mite population and leaf damage in African nightshades.

7.3 Material and methods

7.3.1 Study site

Greenhouse experiments were carried out at Jomo Kenyatta University of Agriculture of and Technology (JKUAT), Juja, Kenya (0° 10′ 48″ S, 37° 07′ 12″ E; 1525 m.a.s.l.) between January and June 2015. Temperatures of 25±6°C were recorded using a Tinytag Gemini data logger (TGP-4017, UK).

7.3.2 Plant materials

Seeds of *S. scabrum*, Olevolosi variety were obtained from the World Vegetable Centre (AVRDC, Arusha, Tanzania) while those of *S. scabrum* varieties, Abuku1 and Abuku2 were obtained from Professor Mary Abukutsa of Jomo Kenyatta University of Agriculture and Technology.

7.3.3 Experiment layout

The Screen house experiment was laid out as a factorial experiment with three fertilizer and three water treatments replicated thrice and three lines of *S. scabrum*. Seedlings nightshade varieties were raised in greenhouse benches by planting 8-10 seeds in 3 kg plastic pots containing 2:1 mixture of sterilized river sand and red soil. At 6 weeks after sowing seedlings were transplanted in pots and thereafter fertilizer treatments were applied weekly while water levels were maintained daily. Three fertilizer treatments, full strength (1) as the control, half strength (0.5), and quarter strength (0.25) concentrations of Hoagland's nutrient solution were used. The solution was prepared by first making stock solutions from macro and micro nutrients from which a working solution was then made as described by (Hoagland & Arnon, 1950). The stock solution with Macronutrients was made from 202g/L of KNO3, 493g/L MgSO4.7H2O, 136g/L KH2PO4, 236g/L Ca(NO3)2.4H2O and 80g/L NH4NO3 salts. For micronutrients stock solution, 1.81g/L MnCl2.4H2O, 0.0051g/L CuSO4, 0.22g/L ZnSO4.7H2O, 0.12g/L Na2 MoO4 x 2H2O, 2.86g/L H3BO3 and 15g/L FeSO4.7H2O salts were used. Three water regimes i.e. 40%, 60 %, and 80% field capacity were used. Soil moisture levels were measured using a Time Domain Reflectometer (TDR) (Soil moisture Corporation California, USA). *T. evansi* mites were obtained from a colony maintained on *S. scabrum* in a rearing room at the International Centre of Insect Physiology and Ecology (ICIPE) at a temperature of 23±2°C, 60-70% relative humidity and a 12:12 light: dark photoperiod. Heavily infested nightshade leaves were excised from the colony at ICIPE and transported to the greenhouse in Khaki bags. Three weeks after transplanting, 20 female mites aged 2-4 days old were introduced to each nightshade plant in the screen house after scouting to confirm that the crop was free from mites.

7.3.4 Mite count

Each treatment had 36 plants and 3 plants were randomly sampled every week for seven weeks. On each plant, top, middle and bottom leaves were picked and the numbers of motile stages of *T. evansi* on each leaf were counted. Two weeks after the African nightshade plants were artificially infested with mites, three leaves per plant i.e. top, middle and bottom leaves were harvested weekly for seven weeks, placed into khaki bags and transported into the laboratory. All motile stages of mites from each leaf were then counted using a dissecting microscope at x25 magnification.

7.3.5 Leaf damage

Mite damage on the leaves was scored using 0-5 scale described by (Hussey & Parr 1963) based on numerical values of the degree of spider mite damage to leaves: 0=no damage, 1=1-20%, 2=20-40%, 3=40-60%, 4=60-80% and 5=80-100% leaf damage.

7.3.6 Plant growth

For plant growth assessment whole plants were uprooted after leaf samples for mite count and leaf damage was assessed. Plant parts were separated into roots, stem, and leaves and packed into paper bags and transported in the laboratory. Leaf area was measured using a LI-COR Li-3000 leaf area meter (LAI-2000 Plant Canopy Analyzer PCA, LI-Cor, Lincoln, NE, USA). Leaves, stems, roots and flower where present were oven dried at 50°C for a week and thereafter their dry weights recorded and used to determine relative growth rate, leaf area ratio, leaf weight fraction, specific leaf area and root-shoot allometry.

7.3.7 Determination of alkaloid content

Alkaloid content in the leaves of *S. scabrum* varieties was determined using an alkaline precipitation gravimetric method previously described by Harborne (1973). Five (5)grams powder of dried leaf sample was dispersed in 200ml of 10% acetic acid in 96% ethanol and allowed to stand for 4hours at 28ºC in an oven. The mixture was then filtered using Whatman filter paper No. 42 and the filtrate concentrated 50ml in a rotary evaporator (Model No. RE100 from Bibby Sterilin Ltd., UK). Concentrated aqueous ammonium hydroxide was then added dropwise to precipitate the alkaloids. The precipitate was collected on a weighed Whatman filter paper No. 42 then rinsed by pouring 1% ammonia solution over the precipitate. The precipitate was dried in an oven at 80ºC overnight and its final weight was taken. The alkaloid content was calculated by (Weight of filter paper with precipitate - Weight of empty filter paper). This was then converted into a percentage of the initial dry weight of the sample. Samples from each fertilizer and water regimes were replicated thrice.

7.3.8 Statistical analysis

Count data on the number of mites were log10 transformed while damage which was recorded in percentages were angularly transformed before analysis of variance was carried out using a linear mixed model in R version 3.4.1 (R Core Team, 2017). Differences in means between groups were separated *post hoc* using Tukey test with a Bonferroni correction for multiple comparisons. Plant growth analysis was carried out using software developed by (Hunt, Causton, Shipley, & Askew, 2002) in which the leaf area, dry weights of leaves, stems, and roots of the 6^{th} and 10^{th} WAT interval were used to estimate growth parameters. Correlation analysis between alkaloids, mite populations, and leaf damage was carried out using the Pearson statistic.

7.4 Results

7.4.1 Effects of fertilizer and water regimes on *T. evansi* populations

The combined effect of variety, plant age and nutrition regimes significantly influenced the mite population ($F_{(96, 378)} = 1.33$, p=0.03). There were differences in varieties ($F_{(2, 378)} = 55.04$, p<0.001) with more mites on Olevolosi (178.90±8.83) than Abuku1 (169.15±8.42) and Abuku2 (166.29±8.6). Mite population increased ($F_{(6, 378)} = 6972.60$, p<0.001) with a mean of 21.56±0.86 in the 6th week after transplanting to 303.17±7.85 in the 12th week. Nightshades grown at 40% water field capacity (187.12±9.96) had more mites than in 80% (162.10±8.25) and 60% (132.70±6.35) per leaf. Also, nightshades grown in concentration 1 nutrient solution had more mites (184.50±9.04) than 0.5(170.53±8.62) or 0.25 (160.31±8.12). Mite populations at the 10th week after transplanting are presented in Figure 7-1.

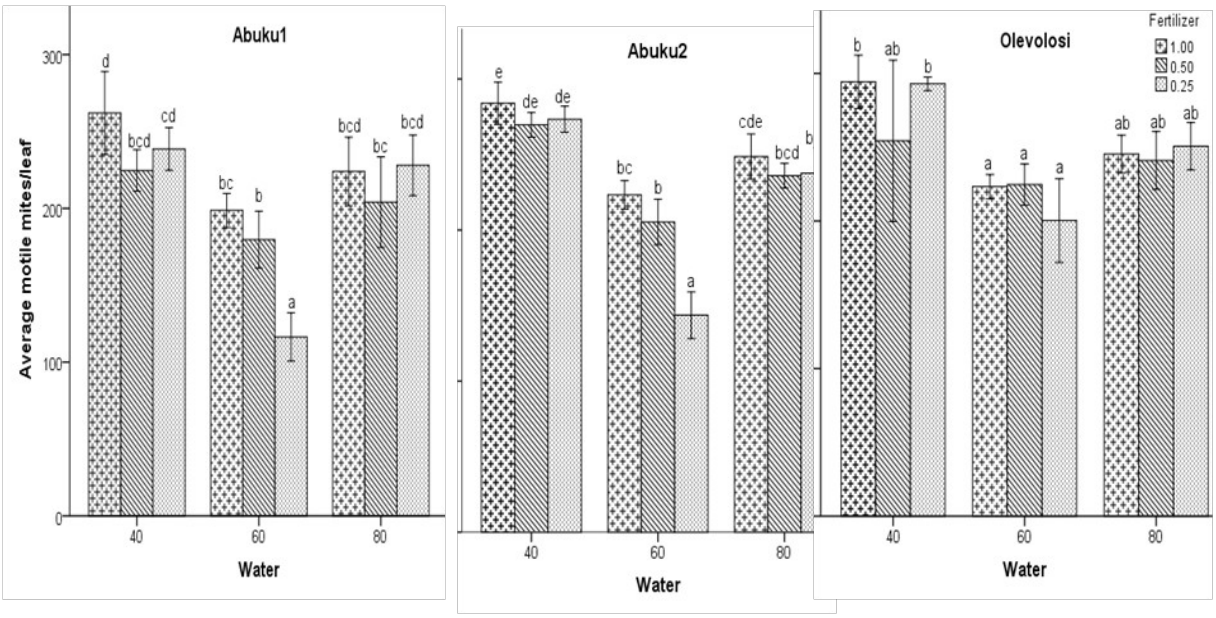

Figure 7-1: Mean number of T. evansi on S. scabrum varieties Abuku1, Abuku2, and Olevolosi at the 10th week after transplanting. Means followed by the same letter within a variety are not significantly different, N= 3

7.4.2 Effects of water and fertilizer regimes on leaf damage

Fertilizer and water regimes influenced the severity of *T. evansi* damage ($F_{(8, 378)} = 158.93$, $p<0.001$) on African nightshades. Fertilizer and water regimes also significantly affected leaf damage within each variety; Abuku1 ($F_{(8, 18)} = 6.07$, $p=0.001$), Abuku2 ($F_{(8, 18)} = 5.33$, $p=0.002$) and Olevolosi ($F_{(8, 18)} = 5.17$, $p=0.002$) (Figure 7-2). Plants receiving a nutrient solution of 0.25 concentrations had higher leaf damage than those receiving 0.5 and full-strength nutrient solution. However, plants that received 80% water levels had reduced damage than those plants that received low water levels of 60% and 40% (Figure 6-2).

There was a difference in the level of damage caused by *T. evansi* between the *S. scabrum* varieties ($F_{(2, 378)} = 53.72$, $p<0.001$) with Olevolosi (33.76±1.74) suffering less damage than Abuku1 (39.58±2.00) and Abuku2 (39.74±2.02) Table 7-2.

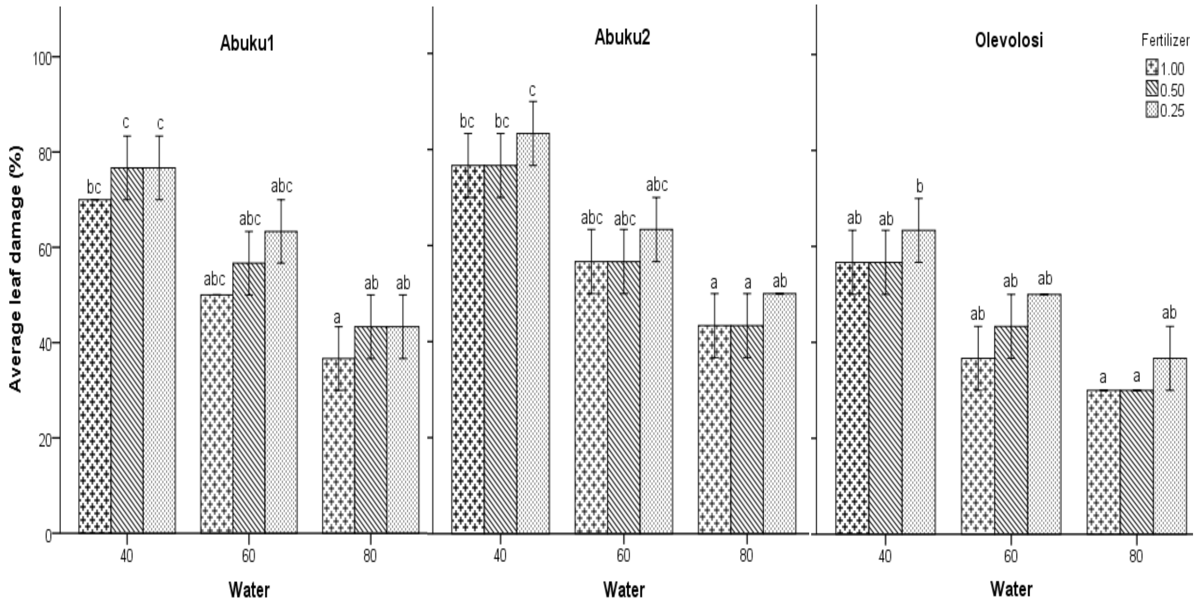

Figure 7-2: Mean number of T. evansi on S. scabrum varieties Abuku1, Abuku2, and Olevolosi at the 10th week after transplanting. Means followed by the same letter within a variety are not significantly different. N= 3

7.4.3 Effects of variety and plant age on leaf damage

Leaf damage was significantly different between weeks ($F_{(6, 378)}$ = 1251.18, p<0.001) increasing from 10% in the 6th week after transplanting to 69% in the 12th week after transplanting. The damage levels in the initial two weeks of sampling were not different (Table 7-1). There was a difference in the level of damage caused by *T. evansi* between the *S. scabrum* varieties ($F_{(2, 378)}$ = 53.72, p<0.001) with Olevolosi (33.76±1.74) suffering less damage than Abuku1 (39.58±2.00) and Abuku2 (39.74±2.02) Table 7-1.

Table 7-2. Percentage of leaf damage on African nightshade varieties by *Tetranychus evansi* from the 6th to 12th weeks after transplanting. Means followed by the same small letter in a row are not significantly different and means followed by the same capital letter are not different, N=27.

	Variety			
Week	Abuku1	Abuku2	Olevolosi	Mean
6	10.00±0.00a	10.00±0.00a	9.63±0.37a	9.88±0.12a
7	9.63±0.37a	10.00±0.00a	10.00±0.00a	9.88±0.12a
8	23.33±2.61b	24.07±2.78b	21.11±2.22b	22.84±1.46b
9	36.67±2.61c	37.41±2.64c	31.48±3.18b	35.19±1.64c
10	57.41±3.22d	61.11±3.26d	44.81±2.74c	54.44±1.92d
11	67.78±3.43de	65.56±3.43d	55.93±2.98d	63.09±1.96e
12	72.22±2.89e	70.00±3.20d	63.33±3.69d	68.52±1.92f
Mean	39.58±2.02A	39.74±2.00A	33.76±1.73B	37.69±1.12

7.4.4 Effects of water and fertilizer regimes on the alkaloid content

There was no difference in total alkaloids between the three varieties ($F_{(2, 162)}$ =0.52, p<0.60) and hence the data was pooled in subsequent analysis. However, there was a significant difference in total alkaloid content among fertilizer and water regimes ($F_{(8, 162)}$ =29.93, p<0.001). Plants receiving water level of 80% field capacity together with 0.25 concentration of the nutrient solution had the highest alkaloid contents while those plants that received 40% field capacity had the lowest alkaloid content (Figure 7-3).

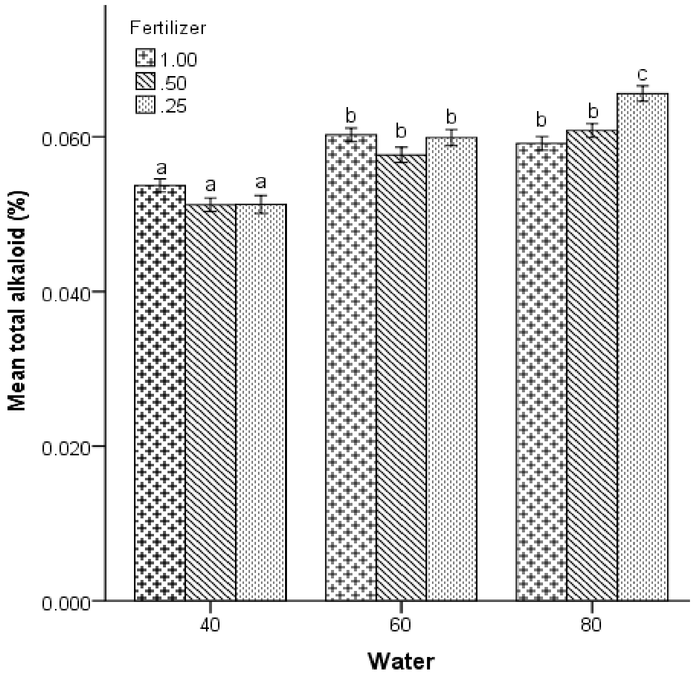

Figure 7-3. Percentage of total alkaloids on *S. scabrum* grown under 40%, 60%, 80% soil moisture and 1, 0.5 and 0.25 fertilizer concentration regimes. Means followed by the same letter within a week are not significantly different. (ANOVA; Means compared using Tukey test, p=0.05, n=27).

Plantage also affected total alkaloids ($F_{(2,\ 162)}$ =24.51, $p<0.001$) whereby total alkaloid contents in the leaves reduced with plant age. In the 6[th], 8[th] and 10[th] weeks after transplanting average total alkaloid contents were 0.060%, 0.058%, and 0.056% respectively. The total alkaloid content for the 9 fertilizers and water regimes within each week are presented in Figure 7-3.

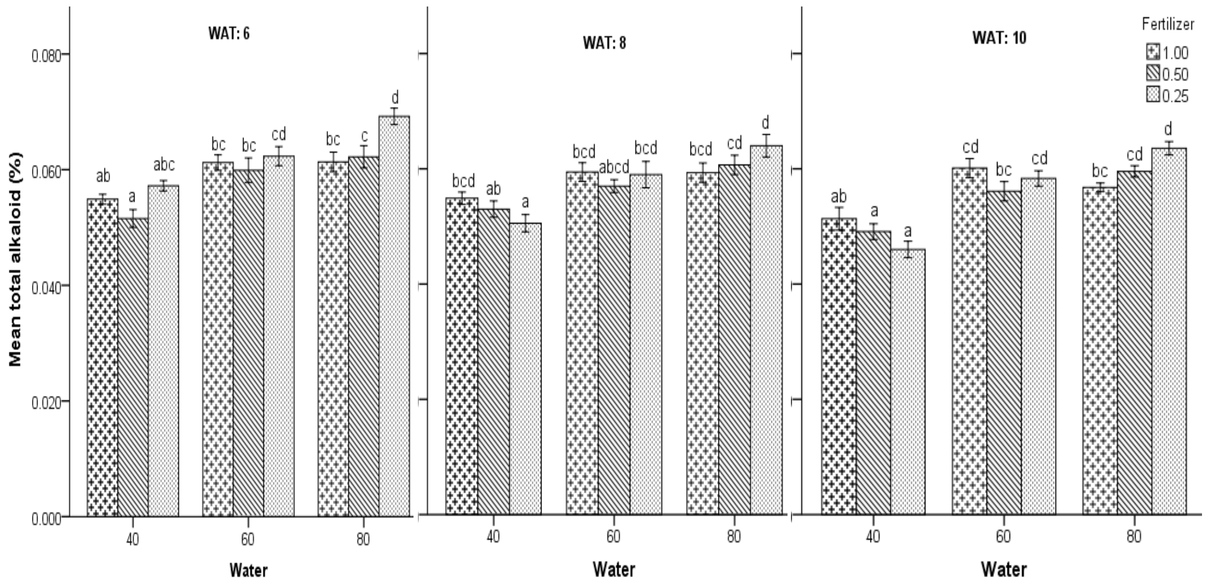

Figure 7-4. Mean percentage of total alkaloids from *S. scabrum* varieties at the 6th, 8th and 10th week after transplanting. Means followed by the same letter within a week are not significantly different, N=9.

7.4.5 Impact of alkaloid content on mite population and leaf damage

Overall, there was a negative correlation between alkaloid content (M=0.058 SD=0.006) and the number of mites per leaf (M=118.05 SD=89.86), r=0.35, p<0.0, n=243. Among the treatments, the extreme regimes had significantly negative correlations i.e. 80% moisture level with both complete (1) and 0.25 nutrient solution concentrations as well as and 40% moisture level with 0.25 nutrient solution concentration (Table 7-3).

There were significant negative correlations between alkaloid content found in leaves of African nightshade and the level of damage observed on the leaves for the extreme regimes i.e. 80% moisture level with both complete (1) and 0.25 nutrient solution concentrations as well as 40% moisture level with 0.25 nutrient solution concentrations (Table 7-4).

Table 7-3: Pearson correlations between alkaloid content and mite population in *S. scabrum* at each fertilizer and water regimes, n=27

Water and fertilizer regime			Alkaloid %	Mites
80*1	Alkaloid %	Pearson Correlation	1	-.423*
		Sig. (2-tailed)		.028
	Mites	Pearson Correlation	-.423*	1
		Sig. (2-tailed)	.028	
80*0.5	Alkaloid %	Pearson Correlation	1	-.136
		Sig. (2-tailed)		.499
	Mites	Pearson Correlation	-.136	1
		Sig. (2-tailed)	.499	
80*0.25	Alkaloid %	Pearson Correlation	1	-.507**
		Sig. (2-tailed)		.007
	Mites	Pearson Correlation	-.507**	1
		Sig. (2-tailed)	.007	
60*1	Alkaloid %	Pearson Correlation	1	-.110
		Sig. (2-tailed)		.583
	Mites	Pearson Correlation	-.110	1
		Sig. (2-tailed)	.583	
60*0.5	Alkaloid %	Pearson Correlation	1	-.290
		Sig. (2-tailed)		.142
	Mites	Pearson Correlation	-.290	1
		Sig. (2-tailed)	.142	
60*0.25	Alkaloid %	Pearson Correlation	1	-.277
		Sig. (2-tailed)		.162
	Mites	Pearson Correlation	-.277	1
		Sig. (2-tailed)	.162	
40*1	Alkaloid %	Pearson Correlation	1	-.374
		Sig. (2-tailed)		.054
	Mites	Pearson Correlation	-.374	1
		Sig. (2-tailed)	.054	
40*0.5	Alkaloid %	Pearson Correlation	1	-.310
		Sig. (2-tailed)		.115
	Mites	Pearson Correlation	-.310	1
		Sig. (2-tailed)	.115	
40*0.25	Alkaloid %	Pearson Correlation	1	-.743**
		Sig. (2-tailed)		.000
	Mites	Pearson Correlation	-.743**	1
		Sig. (2-tailed)	<0.001	

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed). N=27

Table 7-4: Correlation between alkaloid content and leaf damage in *S. scabrum* for each regime. n=27

Correlations

Water and fertilizer regime			Alkaloid %	Damage %
80*1	Alkaloid %	Pearson Correlation	1	-.458*
		Sig. (2-tailed)		.016
	Damage %	Pearson Correlation	-.458*	1
		Sig. (2-tailed)	.016	
80*0.5	Alkaloid %	Pearson Correlation	1	-.121
		Sig. (2-tailed)		.546
	Damage %	Pearson Correlation	-.121	1
		Sig. (2-tailed)	.546	
80*0.25	Alkaloid %	Pearson Correlation	1	-.465*
		Sig. (2-tailed)		.015
	Damage %	Pearson Correlation	-.465*	1
		Sig. (2-tailed)	.015	
60*1	Alkaloid %	Pearson Correlation	1	.017
		Sig. (2-tailed)		.931
	Damage %	Pearson Correlation	.017	1
		Sig. (2-tailed)	.931	
60*0.5	Alkaloid %	Pearson Correlation	1	-.267
		Sig. (2-tailed)		.177
	Damage %	Pearson Correlation	-.267	1
		Sig. (2-tailed)	.177	
60*0.25	Alkaloid %	Pearson Correlation	1	-.177
		Sig. (2-tailed)		.377
	Damage %	Pearson Correlation	-.177	1
		Sig. (2-tailed)	.377	
40*1	Alkaloid %	Pearson Correlation	1	-.257
		Sig. (2-tailed)		.195
	Damage %	Pearson Correlation	-.257	1
		Sig. (2-tailed)	.195	
40*0.5	Alkaloid %	Pearson Correlation	1	-.353
		Sig. (2-tailed)		.071
	Damage %	Pearson Correlation	-.353	1
		Sig. (2-tailed)	.071	
40*0.25	Alkaloid %	Pearson Correlation	1	-.551**
		Sig. (2-tailed)		.003
	Damage %	Pearson Correlation	-.551**	1
		Sig. (2-tailed)	.003	

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed). N=27

7.5 Discussion

The relationship between host plant quality and how it affects feeding, food utilization and subsequently arthropod performance determines the success of pest management through manipulation of arthropod performance (Slansky, 2013). In this study, *S. scabrum* grown under 40% water field capacity had a higher mite population than those grown under 60% and 80% soil moisture levels. This concurs with the findings of (Ximénez-Embún et al., 2016) who observed that drought-stressed tomatoes suffered high leaf damage caused by *T. evansi* attributed to an increase in free sugars and amino acids that stimulate feeding and egg-laying in *T. evansi*.

In this study, mite populations were observed to increase mostly with an increase in fertilizer concentration. This agrees with the findings of (Chow et al., 2009) who observed a positive correlation between nitrogen fertilization and spider mites densities in cut roses. This may be as a result of increased plant succulence that occurs when nitrogen is relatively higher than other macronutrients and carbohydrates are used for protein synthesis rather than cell walls (Tisdale & Nelson, 1975). Also, a study on foliage stratas in *Ivy geranium* and *Pelargonium peltatum* found a positive correlation between nitrogen and phosphorus concentrations and mite distribution in plants (Chen et al., 2007). This may be attributed to an increase in nitrogen available to a plant that has been shown to impact population density, fecundity, oviposition, development time and survival of mites (Geddes 2010; Chow et al. 2009).

Plant tolerance to pest damage is dependent on its morphological, physiological and biochemical traits most of which are influenced by plant nutrition (Louda & Collinge, 1992). In this regard, plants grown under optimal nutrition have better physical and chemical properties i.e. larger leaf area for higher photosynthesis as well as developed root system for enhanced nutrient uptake (Carmona et al, 2011). In this study, *S. scabrum* varieties exhibited differential tolerance to *T. evansi* which can be attributed to their traits. For example, Olevolosi variety had a higher mite population probably due to its larger leaves providing more food resources for mites than Abuku1 and Abuku2 with smaller leaves. However, this variety was the least damaged of the three probably due to the high relative growth rate and specific leaf area implying a higher photosynthetic capacity supporting faster growth to compensate for damaged leaf area. Similarly, findings of low damage in African nightshades with high relative growth, specific leaf area, and leaf area ratio were reported by Murungi et al. 2014. Therefore, findings in this study suggest that 80% water field capacity and complete fertilizer regime support a high growth rate in *S. scabrum* thereby compensating for tissue damage and reducing leaf damage levels. Also, Olevolosi variety is observed to be more tolerant of *T. evansi* damage than Abuku1 and Abuku2.

The lowest alkaloid levels were observed in plants grown in the regime containing the low moisture and fertilizer levels. These results concur with the findings reported in *Senecio vulgaris* where water and nutrient deficiencies were shown to reduce total alkaloids (Brown & Molyneux, 1996). This occurrence may be attributed to the fact that alkaloids are nitrogenous compounds and nitrogen availability reduces with soil moisture reduction (Zhang & Wienhold, 2002). Younger plants mostly contained more total alkaloids than older plants and this agrees with an earlier report that alkaloid content is usually higher in young and metabolically active plant tissues than in aged and senescing tissues (Wink, 1988). Furthermore, Paul & Basu, 2006, found *Datura metel*, another Solanaceous plant to have the highest total alkaloids during the rainy season at the flowering stage.

Plants growing under extreme fertilizer and water levels had considerably low mite population and leaf damage with higher alkaloid content in the leaves. Plants exposed to stress growth conditions are known to accelerate nitrate accumulation in plant tissue and slow down protein synthesis. In this case, alkaloid producing plants shift their metabolism towards the accelerated synthesis of alkaloids as a form of nitrogen storage (Ghorbanpour, 2014). Therefore the reduction in protein and increase in alkaloid synthesis might have led to reduced leaf size hence fewer mites per leaf and increased alkaloid bioactivity that could suppress mite populations in the poor regimes. Similar findings have been reported in other crops like roses (Amirjani, 2013) and capsicum (Phimchan, 2012). However, the observation in the highest fertilizer and water regime, of the increased alkaloid content, enlarged leaf area, high mite population but low leaf damage may be an indication of proper plant growth where a balance exists between plant growth and biochemical defense mechanisms including secondary metabolites like alkaloids.

Therefore, farmers of African nightshades should be cognizant of the effects of irrigation and fertilization regimes on mite infestations on the crop and how these regimes can be used to increase yields and manage mite infestations. Consequently, irrigation and fertilization regimes could be incorporated into integrated pest management programs for mite control.

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8 General discussion

African indigenous vegetables are highly nutritious, most have a short growing period and adapt to a wide range of soils and climatic conditions. In East Africa, where levels of malnutrition are high among the rural and urban poor households, AIVs have great potential to improve nutrition. However, AIVs are attacked by several pests leading to major yield losses. Although pest status changes with the season, agro-ecological zones, or even altitude, there is little information on the major pest of AIVs in different zones or seasons of the year. Altitudinal changes impact environmental factors such as temperature, precipitation, wind speed, radiation, and atmospheric turbulences (Barry, 1992). Generally, the rate of temperature decrease with increasing altitude lies between 5.5°C and 6.5°C for every 1000m of ascent in the free atmosphere (Anslow & Shawn, 2002). For most insects, body temperature is dependent on ambient temperatures and a temperature increase of 10°C can cause a two to three-fold increase in their metabolic rate thus changes in population. Precipitation also increases with an increase in altitude and influence the diversity and distribution of insects mainly by supporting diverse vegetation.

This study found out that the Lepidoptera order accounted for the highest damage on amaranth crops with up to ten species observed across regions. Among them *S. recurvalis*, *U. ferrugalis*, *H. bipunctalis* and *S. litorralis* have also been reported in Kenya and Nigeria (Kahuthia-Gathu, 2013), (Aderolu et al., 2013). This also concurs with a survey in Kenya that observed lepidopterans were the major pests but also found *A. octogueae* that was absent in Tanzania (Mureithi et al, 2017). The spread of *S. recurvalis* has been attributed to its ability to adapt to a wide range of climatic conditions (Aderolu et al., 2013) and therefore farmers may need to be more vigilant and manage its populations to avert widespread infestations.

A. fabae, *M. persicae* and *A. craccivora* aphid species occurred in all regions of Tanzania. This finding may offer the identity of aphids that farmers reported to be a major pest in Arumeru district among farmers interviewed by (Keller, 2004). The three aphid species were also observed during a survey carried out in Kenya by (Mureithi, 2018) but he also observed *Toxoptea* sp. as an aphid pest in amaranth. The polyphagous nature of these three aphid species, enables them to survive throughout the year on other crops or weeds.

The red spider mites were the most damaging pests of African nightshades with the *T. evansi* species being the dominant species. The abundance was twice the in the dry season compared to the wet season particularly in the low altitude regions of Pwani and Kilimanjaro. Similar observations were reported in Tabora region of Tanzania, where *T. evansi* is considered a major threat to dry season tomato production (Bagarama, 2014). These findings, confirm that *T. evansi* has spread from where it was first reported by Boubou and his colleagues in 2011. Flea beetles were observed to cause considerable leaf damage in Lushoto district in the low altitude region. Similar concurs with the findings of (Mureithi, 2018) where beetles damage was higher in mid altitude areas in Kenya.

In Ethiopian kale fields, hemipterans mainly sap-sucking aphids and lepidopterans that defoliated the leaves were the most damaging pests. The findings of diamondback moth as a major pest species in the Lepidoptera order in this study confirms reports of up to 92% of farmers in India (Sandur, 2004), 60% in Indonesia (Rauf, 2004) and 89 % in Kenya (Oruku and Ndung'u, 2001) citing the species as a major pest. Among Hemiptera order, the cabbage aphid, *B. brassicae* was the most abundant species. Both Diamondback moth and cabbage aphid are specialists of Brassica plants. This may explain the high populations found in the mid-altitude regions such as Mbeya, Dodoma, and Arusha which are major producers of brassica crops such as cabbage. Also, bagrada bugs whose feeding results in large stippled areas that eventually wilt and die leaving a leaf scotch appearance and mainly damaging old brassica crops were present on crops at seeding stage (Reed et al., 2014). Therefore, farmers in these areas could benefit from practicing crop rotation to break pest cycles and limit population growth. Aphid parasitoids *D. rapae* and *A. colemani* were the most abundant natural enemy corresponding to the high abundance of aphids. Pollen and nectar are considered critical for the fitness and abundance of adult braconid wasps, lace-wings and hoverflies (van Rijn & Wäckers, 2016) which were among the main groups of natural enemies observed during the survey. Therefore, the high abundance of natural enemies in the wet season may be due to the presence of a variety of flowering plants.

Mite oviposition in the laboratory was not influenced by different fertilizer and water regimes which are expected to vary host quality. Therefore other factors may be involved in oviposition in the mite. However, varietal differences were important factors influencing oviposition of the tomato red spider mites and may also emphasis the role of morphological, physiological and biochemical traits of a plant. Therefore, the choice of African nightshade varieties that deter oviposition by tomato red spider mite can a preventative measure in reducing mite infestations and subsequently improving yields and incomes of nightshade growers.

In plants, drought stress changes their metabolism and nutritional value Ximénez-Embún, 2016. In this study, *S. scabrum* grown under low moisture had higher mite population than those grown under moderate and high moisture levels. This concurs with the findings of Ximénez-Embún *et al*. 2016 who observed that drought-stressed tomatoes suffered high leaf damage caused by *T. evansi* and they attributed it to an increase in free sugars and amino acids that stimulate feeding and egg laying in *T. evansi*. Consequently, host plant quality affects feeding and food utilization in arthropods and as a result their arthropod performance

(Slansky, 2013). Therefore, plant nutrition can be explored for pest management through the manipulation of arthropod performance.

Plant tolerance to pest damage is dependent on its morphological, physiological and biochemical traits most of which are influenced by plant nutrition. The lowest alkaloid levels were observed in plants grown in the regime containing the low moisture and fertilizer levels. These results concur with the findings reported in *Senecio vulgaris* in which water and nutrient deficiencies were shown to reduce total alkaloids (Brown & Molyneux, 1996). This occurrence may be attributed to the fact that alkaloids are nitrogenous compounds and nitrogen availability reduces with soil moisture reduction (Zhang & Wienhold, 2002). In this study, plants growing under extreme fertilizer and water levels had considerably low mite population and leaf damage with higher alkaloid content in the leaves. Similar findings have been reported in capsicum (Phimchan et al., 2012). Plants exposed to stress growth conditions are known to accelerate nitrate accumulation in plant tissue and slow down protein synthesis. However, the observation in the highest fertilizer and water regime, of the increased alkaloid content, enlarged leaf area, high mite population but low leaf damage may be an indication of proper plant growth where a balance exists between plant growth and biochemical defense mechanisms including secondary metabolites like alkaloids.

Therefore, farmers should be cognizant of the arthropod pests associated with African indigenous vegetables and use appropriate management measures. Farmers should also ensure African nightshades are well watered and receive adequate fertilizer, particularly during the dry season when the crop is mainly grown under irrigation. This could suppress red spider mite populations hence improve yields.

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Curriculum vitae

Jackline Kendi Mworia was born in Meru, Kenya on the 6th June 1979. She attended and attained the Kenya certificate of primary education at Materi Girls' Centre, Tharaka nithi in 1994. Thereafter, she completed her high school education Materi Girls' High school and was admitted for a Bachelor of Science in Horticulture at Jomo Kenyatta University of Agriculture and Technology, Juja, Kenya from 2000-2014. Upon graduating, she joined Tambuzi Limited as a management trainee and rose to the level of Technical manager where she carried out quality management audits of flower and vegetables aimed at ensuring compliance to good agricultural practices between 2014 – 2009. Afterward, she joined AAA Limited where she worked as a technical manager carrying out internal audits and ensuring adherence to good pack-house practices in the Export of vegetables from October 2009 – June 2010. She was awarded a DAAD scholarship towards a Master of Science in International Horticulture studies at Gottfried Wilhelm Leibniz Universität Hannover from October 2010 – September 2012. For her Master thesis, she investigated the effects of heatwaves on the development of *Brevicoryne brassicae* and *Myzus persicae* and their bacterial endosymbionts and graduated with a major in Phytopathology and entomology. From January 2014, she was awarded a scholarship from BMBF through the HORTINLEA project to undertake her doctoral studies on the major pests of African indigenous vegetables in Tanzania and the impact of plant nutrition on spider mite management at Gottfried Wilhelm Leibniz Universität Hannover and Jomo Kenyatta University of Agriculture and Technology. She has interests in vegetable and flower production, pest management, and entomology. Miss. Mworia is married to John and together they have a daughter Racheal.