WEAVER ANT *OECOPHYLLA LONGINODA* LATREILLE (HYMENOPTERA FORMICIDAE) AS BIOCONTROL AGENT ON MAJOR INSECT PESTS OF CASHEW AND MANGO IN TANZANIA

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EXTENDED ABSTRACT

Experiments to determine the potential of Weaver ants, *Oecophylla longinoda* Latreille (Hymenoptera: Formicidae) as biocontrol agents of major insect pests of cashew and mango were conducted at Naliendele Agricultural Research Institute in Mtwara and Kibaha in the Coast region, during 2012/13 and 2013/14 fruiting seasons. Cashew is attacked by Coconut bugs, *Pseudotheraptus wayi* Brown; Mirid bugs, *Helopeltis* spp. and Thrips, *Selenothrips rubrocinctus* Giard. Mango is threatened by several fruit fly species and the mango seed weevils, *Sternochetus mangiferae* (Fabricius); both being quarantine pests. Farmers use synthetic insecticides to control these pests and no alternative measures are available for organic growers. Reliance on chemical control measures has not made it possible to suppress the pests' populations to uneconomic levels. Similarly, dependency on insecticides for the control of *S. mangiferae* during flowering season has not proven very successful. In the current study, the efficiency of *O. longinoda* as bio-control agents was compared with Karate® (lambda-cyhalothrin) and the control plots against Cashew insect pests. On mango, the efficacy of *O. longinoda* was compared with Dudumida (70WDG Imidacloprid) and the control against fruit flies and the *S. mangiferae*. The results indicated significantly lower (P<0.0001) damages for the three cashew pests in the protected trees compared to control. For two seasons, *P. wayi* damage was <5% in protected trees as opposed to 29% and 25% in the unprotected plots; *Helopeltis* spp damage was <3% in protected trees for two seasons as opposed to >8% and >6% in unprotected, and *S. rubrocinctus* damage was <11% in protected trees for both seasons as opposed to >41% and >39% in the unprotected plots in 2012/13 and 2013/14 respectively. Incidences of fruit flies was <6% and <8% in protected trees as opposed to >18% and >24% in the unprotected in 2012/13 and 2013/14 respectively, whereas incidences of *S. mangiferae* was <7% and <8% in protected trees as opposed to >24% and >30% in unprotected trees in 2012/13 and 2013/14 respectively. Throughout the experiments *O. longinoda* was as effective as insecticides in controlling major cashew and mango insect pests. Thus, *O. longinoda* can serve as a substitute to insecticides.

DECLARATION

I, **NASSOR RASHID ABDULLA** do hereby declare to the Senate of Sokoine University of Agriculture that this thesis is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

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LIST OF ABBREVIATIONS AND SYMBOLS

%	Percent
χ^2	Chi-Square
$<$	Less than
$>$	Greater than
±	Plus or minus
≤	Less than or equal to
^{0}C	Degrees Celsius
AD	Anno Domini
CABI	Commonwealth Agricultural Bureaux International (UK)
cm	Centimetres
DANIDA	Danish International Development Assistance
Dr	Doctor
DSCF	Dwass, Steel, Critchlow-Fligner
E	East
EC	Emulsifiable concentrates
EIL	Economic injury level
EPOPA	Export promotion of organic products from Africa
ESA	Eastern and Southern Africa

FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Statistical Databases of the United Nations
FF	Fruit flies
ft	Feet
FWA	Fed weaver ants
g	Gram
h	Hour
ha	Hectare
ICIPE	International Centre for Insect Physiology and Ecology
IHC	International Horticultural Conference
IPM	Integrated Pest Management
kg	Kilogram
L	Litre
m	Metres
m^2	Metre square
MANR	Ministry of Agriculture and Natural Resources
masl	metres above sea level
MAT	Male Annihilation Technique
ml	Millilitres
mm	Millimetres
MMA	Match Maker Associates Limited

MSW	Mango Seed Weeevil
N	North
NARI	Naliendele Agricultural Research Institute
NBCU	National Biological Control Unit
PMD	Powdery Mieldew Disease
RH	Relative Humidity
S	South
SCF	Small and Medium Enterprise Competitiveness Facility
SE	Standard error
spp	Species
SSA	Sub-Saharan Africa
SUA	Sokoine University of Agriculture
TMB	Tea Mosquito Bug
USD	United States Dollar
USDA-APHIS	The United States Department of Agriculture, Animal and Plant Health Inspection Service
UWA	Unfed weaver ants
vs	Versus
W	West
WDG	Water dispersible granules
WP	Wettable Powder

CHAPTER ONE

1.0 GENERAL INTRODUCTION AND LITERATURE REVIEW

1.1 Cashew Taxonomy, Origin and Distribution

The Cashew tree, *Anacardium occidentale* L., (Sapindales: Anacardiaceae), is a perennial crop and one among members of the *Anacardiaceae* family of plants (Azam-Ali and Judge, 2006). It is a tropical nut tree crop that serves as a source of food, income, industrial raw materials and foreign exchange earnings for many countries of Africa, Asia and Latin America (Adeigbe *et al.,* 2014). The tree is native to Brazil, but has spread to other parts of tropical South and Central America, Mexico and the West Indies in the 16th century (Mitchell and Mori, 1987; Orwa *et al.,* 2009; Azam-Ali and Judge, 2006). The crop was originally introduced by Portuguese travellers during sixteenth century mainly for afforestation, checking soil erosion on the coastal areas of Tanzania, Kenya, Mozambique and Nigeria (Woodroof, 1979). For over 400 years after introduction, cashew trees were exploited mainly for apples, no commercial value was attached to the nuts (Aliyu, 2012).

Cashew production gradually gained importance and is now cultivated commercially for its nuts and other products in the continents of Asia, Africa and South America. Asiatic zones mainly include India, Vietnam and Indonesia as the leading cashew producing countries followed by Philippines, Malaysia, Thailand and Sri-Lanka. African countries producing cashew are Côte d'Ivoire, Nigeria, Tanzania, Mozambique, Kenya, Benin, Guinea-Bissau, Mozambique, Ghana, Senegal and Madagascar. Latin American countries producing cashew consist of Brazil, Columbia, Costa Rica, Honduras and Salvador. (Azam-Ali and Judge, 2006; John *et al.,* 2015). Africa accounts for 33.4% of the world cashew producing area and 26.4% of the world cashew nut production (FAO, 2006).

1.2 Description of the Cashew Plant

The cashew tree is a tropical evergreen, resistant to drought, unexacting as to soil (although it prefers deep, sandy soil) (Azam-Ali and Judge, 2006). It is a fast growing, perennial tree with an extensive root system (Dorthe, 2003) Under ideal tropical conditions the cashew is an attractive, erect, 20 – 35 ft. evergreen tree with smooth brown bark and a dense, symmetrical, spreading canopy. Branching occurs very low on the trunk, with the lowest limbs often touching the ground where they can take root (John *et al.,* 2015). It grows for about 25 – 30 years producing an economic yield from the early stages of its growth (Mitchell and Mori, 1987). Where conditions are less than optimal, the tree grows to no more than 15 to 25 ft. and can develop an ill-defined trunk and a spreading, straggly growth habit (John *et al.,* 2015). There are two main cashew tree-types namely giant, which are large, vigorous trees, usually flowering in their third year from planting, and the dwarfs, which are smaller trees that begin to bloom and fruit in their second or third year from planting and may bloom more than once per year. Cashew plants reach full bearing from 10 to 30 years (Dorthe, 2003).

1.3 Climatic and Soil Requirements

Cashew trees grow in a wide range of climates between the latitudes of around 25 ° north or south of the equator (Wait and Jamieson, 1987). Close to the equator, the trees grow at altitudes of up to about 1500 metres above sea level, but the maximum elevation decreases to sea level at higher latitudes. Although cashew can withstand high temperatures, a monthly mean of 25 ^{0}C is regarded as optimal (Dorthe, 2003; Wait and Jamieson, 1987). Yearly rainfall of 1 000 mm is sufficient for production but 1 500 to 2 000 mm can be regarded as optimal (Wait and Jamieson, 1987; Orwa *et al*., 2009). More important than the amount of rain is its distribution throughout the year. It is essential that the period from flowering up to harvest coincide with a dry time of the year. Rain during the flowering season causes flower abortion due to anthracnose and powdery mildew diseases (Wait and Jamieson, 1987). Well-distributed rainfall tends to produce constant flowering, but a well-defined dry season induces a single flush of flowering, early in the dry season. During harvesting, while nuts are on the ground, rain and overcast weather causes the nuts to rot or start germinating. Nuts germinate within four days if left lying on wet soil.

Established cashew trees in deep soil have a well-developed, deep root system, allowing trees to adapt to long dry seasons (Wait and Jamieson, 1987). It is is a strong plant that is renowned for growing in soils, especially sandy soils that are generally unsuitable for most other fruit trees (Tetra Tech ARD, 2014). Best growth and production occur in deep, well-drained sands or loams. In deep friable soils, full development of the extensive lateral root system occurs, and the deep taproot system reaches several metres in length and can sustain the tree through long dry seasons (Wait and Jamieson, 1987; Dorthe, 2003). Cashew also thrives on pure sandy soils, although mineral deficiencies are more likely to occur. Water stagnation and flooding are not congenial for cashew. Heavy clay soils with poor drainage and soils with pH more than 8.0 are not suitable for cashew cultivation. Excessive alkaline and saline soils also do not support its growth (NARI, 2010).

1.4 Importance of Cashew Crop

Cashew is an important source of livelihood, food security and income for more than five million smallholder farmers in Sub-Saharan Africa (SSA) (ICIPE, 2011). Drought tolerance and its ability to grow on poor soils and to be intercropped with food crops make it an ideal product for smallholder farmers (Mitchell, 2004). Cashew is grown in diverse agro ecological landscapes in Tanzania extending from 0 – 800 metres above sea level (Martin *et al.,* 1997). It is an economically important cash crop for many rural households in Tanzania (Agboton *et al.,* 2013). Cashew is the third important export crop in Tanzania, after coffee and cotton (Ndlovu, 2011).

Cashew serves as an important export crop for its potential as a major source of income for estimated 250,000 small-scale farmers in the southern coastal region where the regions of Mtwara, Lindi and Ruvuma account for 80 – 90% of Tanzania's marketed cashew crop (Martin *et al*., 1997). Mtwara region produces 71% of the total raw cashew output in the country followed by Lindi (18%), Coast (8%) with the remaining 3% coming from the minor producer regions (mainly Ruvuma and Tanga) (Kilama, 2013). About 80 – 85% of the total output is exported raw and 15 – 20% is processed locally for both domestic and international markets (Fitzpatrick, 2012).

1.5 Contribution of Cashew in Cash Income Earnings

Cashew nuts are very important to Tanzania's economy. It is an important source of livelihood, food security and income for many smallholder farmers in SSA and contributes 50 – 90% to their total farm income (USITC, 2007). It therefore contributes to rural livelihoods of over 5 million smallholders in SSA which are involved in its production, processing and marketing (USITC, 2007). They generate an average of USD 74m per year in foreign exchange earnings, serving as Tanzania's leading crop in agricultural export (Table 1.1).

Table 1. 1 Cashew Export Earnings for Three Selected Cropping Seasons

Croppoing season	Production (metric tons)	Export (tons)	% exported as raw	Earnings in USD Million
2005/06	77,446.38	66,708.00	86.13	75
2007/08	99,106.72	75,887.90	76.57	70
2010/11	121,134.97	112,374.00	92.77	140

Sources: CBT (2010), FAOSTAT (2011), TIC (2005), UNIDO (2011)

1.6 Constraints in Cashew Production

The enormous decline in cashew production in SSA, Tanzania in particular is greatly attributed to damage and losses caused by insect pests and diseases at different stages of its growth and development (Maruthadurai *et al.*, 2012). Biotic constraints particularly, sap sucking insect pests and the fungal diseases (powdery mildew) (PMD), *Oidium anacardii* (Noack) have largely contributed to the low yields (NARI, 2010). These pests can lead to 60–100% yield losses depending on the variety, location and season (ICIPE, 2011). Insect pests and diseases may sometimes cause complete yield loss and the intensity of their attack varies with locality, variety and the seasons (Agboton *et al.*, 2013).

1.7 Cashew Insect Pests

Production of cashew in SSA is mostly impaired by insect pest complexes (Hammed *et al.*, 2008). Cashew is attacked by more than 60 different insect species throughout its growth period (Dwomoh *et al.*, 2008a). In Tanzania, the most important insect pests include the coreid coconut bug, *Pseudotheraptus wayi* Brown (Hemiptera: Coreidae), the mirid bugs, *Helopeltis anacardii* Miller, and *H. schoutedeni* Reuter (Hemiptera: Miridae), and thrips, *Selenothrips rubrocinctus* Giard, the dominant species in the study area which suck and feed on new tender shoots, flower panicles and young developing fruits (NARI, 2010). The extent of damage caused by these pests varies with location, variety and management practices (Dwomoh *et al.*, 2009).

1.7.1 The coconut bugs

The coreid coconut bug, *Pseudotheraptus wayi* Brown (Heteroptera: Coreidae) is a major pest of a wide range of economically important agricultural crops in Eastern and Southern Africa (ESA) (Egonyu *et al.*, 2014). *Pseudotheraptus wayi* attacks Cashew (*Anacardium occidentale* L.), Coconut (*Cocos nucifera* L.), Macadamia (*Macadamia integrifolia* Maiden and Betche), Carambola (*Averrhoa carambola* L.), Pecan (*Carya illinoinensis* Wangenh), Cinnamon (*Cinnamomum verum* J. Presl), Loquat (*Eriobotrya japonica* Thunb.), Mango (*Mangifera indica* L.), Avocado (*Persea Americana* Mill.), Guava (*Psidium guajava* L.), and Cocoa (*Theobroma cacao* L.) (Martin *et al.*, 1997; Mitchell, 2000; CABI, 2005; Hill, 2008; Nyambo, 2009). Results from previous studies reported that damage of up to 99.8% on Coconut (Way, 1953), 52.4% on Guava (Van Der Meulen, 1992), 76.2% on Avocado fruits (Van Der Meulen and Schoeman, 1994), and 80% on cashew nut (Nyambo, 2009) were attributed to *P. wayi*. Both nymphs and adults feed by sucking sap from the host plants, causing wilting and necrosis of young stems, leaves, inflorescences, and fruits as they suck sap and inject toxins into the host tissues (Mitchell, 2000; Hill, 2008). Heavily attacked young nuts shrivel, dry and blacken before falling off (Plate 1.1). Feeding points becomes sunken spots and mature kernels will show black and sunken spots, which lowers their market value (NARI, 2010). Effective management of *P. wayi* currently relies on application of insecticides such as lambda cyhalothrin, and endosulfan (Martin *et al.*, 1997; Mitchell, 2000; CABI, 2005), but these chemicals can be very hazardous to human and environmental health (Peng *et al.*, 2014).

Plate 1.1 *Pseudotheraptus wayi* damage on developing shoot (left) and *P. wayi* damage on apple and developing nut (right).

Sources: Peng *et al.*, 2008 (left); Abdulla *et al.*, 2012.

1.7.1.1 Biology of *P. wayi*

Oviposition commences about three weeks after the first mating and eggs hatch 9 – 13 days later (Varela, 1992). Eggs are laid singly at a rate of two to three per day, for a total lifetime fecundity of 74 – 100 eggs per female (Way 1953; Mitchell, 2000). The egg stage lasts for approximately seven days (Bruwer, 1992; De Villiers, 1992). Development of *P. wayi* from egg passes through five instars during which the nymphs are morphologically very similar with their characteristically long antennae. Adults of *P. wayi* are strong fliers with well developed wings. Adults are approximately 15 mm in length and 4 mm in width, with males slightly smaller than females (De Villiers, 1992).

The female lays on average 80 eggs and the life cycle from egg to adult lasts 31 – 48 days, depending on temperature (Bruwer, 1992). The adult life span of *P. wayi* ranges from73 – 84 days at 24.6^{0}C (Way 1953; Wheatley 1961; Mitchell, 2000; CABI, 2005). Nine or more generations per year can occur.

1.7.2 Tea mosquito bugs

Tea mosquito bugs (TMB), *Helopeltis anacardii* Miller and *H. schoutedeni* Reuter (Hemiptera: Miridae) are among the most destructive pests of cashew causing damage to young tender shoots, inflorescence, immature nuts and apple of various stages of crop development (Jalgaonkar *et al.*, 2009; Asokan *et al.*, 2012). The nymphs and adults suck the sap from tender shoots, inflorescence, immature nuts and apple. The saliva of the insects is very toxic and the site of attack is marked by brown to black lesions (NARI, 2010). Previous studies indicated that under very severe cases of attack by TMB, yield losses of up to 100% may be recorded (Jalgaonkar *et al*., 2009**)**. Population levels of different *Helopeltis* spp. fluctuate throughout the year depending on the environmental factors, age and attractiveness of cashew and other host plants in the vicinity, but in some cases build up in numbers is synchronized with the emergence of new foliage (Stonedahl and Dolling, 1991). Typical feeding damage affects the leaves and stems on new shoots, the inflorescence panicles, and the developing nuts that becomes darker (Plate 1.2) with age as the tissue around the point of attack dies (Srikumar and Bhat, 2013). Damaged immature nuts shrivel; while near mature nuts develop a blistered or scabby appearance. Infestations during the early stages of fruit set often result in immature fruit drop (Stonedahl and Dolling, 1991).

Plate 1.2 *Helopeltis* attacking developing shoot (left) and developing nut damaged by *Helopeltis* species (right)

Sources: Abdulla *et al.*, 2012 (left); Peng *et al.*, 2008 (right)

1.7.2.1 Biology of *Helopeltis anacardii*

Helopeltis anacardii lay their eggs on young and succulent tissues near the tips of leaves, inflorescence and fruits. Each female bug lays, on an average, 50 eggs. The incubation period of the egg is on an average five to seven days, at a temperature range of 24 – 32^{0}C and relative humidity of 50 – 100 per cent. About 60% of the eggs normally hatch out as nymphs. Its life cycle consists of five nymphal instars (Hill, 2008). Nymphs and adults attack young and tender leaves, shoots, flowers and fruits (nuts and apples). The saliva of the insects is very toxic and the site of attack is marked by lesions (brown to black in colour). Severe attack of the shoot may cause dieback and heavily infested trees can be recognized from a distance by their scorched appearance (NARI, 2010; Hill, 2008). The total development life cycle, including the twelve day pre-oviposition period, takes about 48 days (Hill, 2008).

1.7.2.2 Biology of *Helopeltis schoutedeni*

Helopeltis schoutedeni eggs that hatch after two weeks are laid in plant tissue singly or in small groups, often with filaments exposed (Ambika and Abraham, 1985; Dwomoh *et al.,* 2008c). Similar to *H. anacardii*, the life cycle of *H. schoutedeni* consists of five nymphal instars (Dwomoh *et al.,* 2008c; Hill, 2008). The total nymphal period is about three weeks and the whole life cycle from egg to adult takes about 24 days (Dwomoh *et al.*, 2008c). The nymphal stages develop faster and the rate of survival is higher when fed on fruits compared to feeding on flushing shoots or panicles (Dwomoh *et al.*, 2008b).

1.7.3 Thrips species

Nymphs and adults can be found in colonies on the lower surface of leaves. They feed by sucking sap on the tender portion of leaves, flowers, floral branches, nuts and apples (Maruthadurai *et al.*, 2012). The rasping and feeding injuries by *S. rubrocinctus* result in scabs on floral branches, nuts and apples. Cracks may also be observed on severely infested apples (Plate 1.3). Infestation on developing nuts results in the formation of shriveled, corky layer on the nuts resulting in malformation and immature drop. The affected nuts turn black and become unattractive (Patil and Dumbre, 1985). Shedding of leaves and stunting of growth of trees occur under severe cases of *S. rubrocinctus* infestations (Maruthadurai *et al.*, 2012). Studies in Australia indicated that, cashew nuts showing thrips damage by more than 51% of the nut surface had a 17–32% reduction in the weight of the raw nut and a 35–53% reduction in kernel weight compared to undamaged nuts (Peng *et al.*, 2008).

Plate 1.3 Severe *S. rubrocinctus* damage on apple and nut

Source: Abdulla *et al.*, 2013

Heavily infested trees exhibit sickly and faded appearance which can be recognized even from a distance. Young trees suffer comparatively more than the matured trees during summer months. Severe drought coupled with reduced moisture content in leaves favour thrips development at a faster rate. Its population flourishes with increase in the temperature during hot weather season. The population of thrips decline with the commencement of rains (Azam-Ali and Judge, 2006). In affected trees, spraying of water twice or thrice during thrips out break helps to reduce its population load appreciably.

1.7.3.1 Biology of *S. rubrocinctus*

The biology of cashew thrips *S. rubrocinctus* was explained by Maruthadurai *et al*., (2012). The eggs are laid on the lower surface of leaves by inserting them singly in the tissues along the mid rib of tender leaves. Eggs are reniform (kidney shaped) and hyaline when laid but turn pale yellow just before hatching. The eggs hatch in about four to six days. The nymphs are pale yellow and wingless. They moult two to three times passing through three to four instars in 12 – 18 days according to the prevailing temperature. Full grown nymphs seek sheltered places and then pass through two resting stages called pre-pupa and pupa. Pupal period lasts for six to ten days. Winged dark-brown adults emerge which have mandibular and maxillary stylets similar to those of nymphs. The female can oviposit soon after emergence and may produce 30 – 50 eggs during her life of about four to five weeks.

1.8 Management Tactics for Cashew Sap-Sucking Insect Pests

Due to the devastating effect of insect pests of cashew at different stages of development, the main management approach used by farmers relies on calendar-based applications of Karate (lamda cyhalothrin), a synthetic pyrethroid together with her generics, which have been proved to be very effective against target pests. Insecticide spray is usually repeated at three-week intervals or when new infestations become apparent (NARI, 2010). Although insecticides can significantly reduce sap-sucking insect pest's damage, the disadvantages are numerous. These include adverse effect on non target species, pesticide resistance, pest resurgence, secondary pest outbreaks and environmental contamination and negative effects on the health of the farmers, who often lack adequate and the necessary protective gears (Saini *et al.,* 2014; Frank *et al.*, 2015). In order to develop sustainable and economically viable alternative to pest management, agricultural systems should be designed in a way that pests do not build up to a level that they cause significant damage to the crops (Frank *et al.*, 2015).

1.9 Mango Taxonomy, Origin and Distribution

The mango tree, *Mangifera indica* L. is a member of the family Anacardiaceae. This family comprises many other valuable trees such as the cashew and the pistachio nut. The genus *Mangifera* contains several other species that bear edible fruits such as *Mangifera caesia, M. foetida, M. odorata* and *M. pajang*. However, *M. indica*, the mango, is the only species that is grown commercially on a large scale (Griesbach, 2003). Other edible *Mangifera* species generally have lower quality fruit and are commonly referred to as wild mangoes (Ian, 2006).

Mango crop is native to India, Bangladesh, Myanmar and Malaysia, but it had spread and can be found growing in more than 60 other countries throughout the world (Salim *et al.*, 2002). Because of its attractive appearance and the very pleasant taste of selected cultivars, it is claimed to be the most important fruit of the tropics (Griesbach, 2003). Currently, mango cultivation has extended to several other parts of the world including Africa, the Americas and the Caribbean region (Al-Najada and Al-Suabeyl, 2014).

Mango is the most widely distributed of all fruits in Tanzania and rather traditional crop. The major growing areas are mainly in the coastal zone (Dar es Salaam, Coast and Tanga) but also in Morogoro, Kilimanjaro and Tabora regions (SCF and MMA, 2008). Mango is predominantly a smallholder crop in Tanzania, often produced at subsistence level with minimum inputs in terms of crop management. Mango orchards are normally small, not exceeding 2 – 5 hectares of land (SCF and MMA, 2008).

1.10 The Mango Plant and the Fruit

The mango tree was described by Griesbach, (2003). It is a deep-rooted, evergreen plant which can develop into huge trees, especially on deep soils. The height and shape varies considerably among seedlings and cultivars. Under optimum climatic conditions, the trees are erect and fast growing and the canopy can either be broad and rounded or more upright. Seedling trees can reach more than 20 m in height while grafted ones are usually half that size. The tree is long-lived perennial plant with some specimens known to be over 150 years old and still producing fruits. Mango fruits of the various cultivars differ greatly in shape, size, appearance and internal characteristics. The fruit is a fleshy, varying in size from 2.5 – 30 cm long, may be kidney-shaped, ovate or round and weigh from approximately 200 g to over 2000 g. The leathery skin is waxy and smooth and when ripe entirely pale green or yellow marked with red, depending on the cultivar.

1.11 Climatic and Soil Requirements

Mango tree is best adapted to a warm tropical monsoon climate with a pronounced dry season (>3 months) followed by rains. The crop is successfully grown on a wide range of soils and grows well in sandy soils at the coastline. The essential prerequisites for good development of the trees are deep soils (at least 3 m), appropriate rainfall (500 – 1000 mm), good drainage, suitable altitude (0 – 1200 m) and preferably a pH value of between 5.5 and 7.5 (Griesbach, 2003)

Optimum growth and productivity is attained at 20 – 26^0 C. Temperatures exceeding 40^0C may lead to sunburn of fruits and stunting of tree growth. Rainfall of 500 – 1000 mm at the right time of the year is sufficient for successful cultivation. However, mango cannot do well in areas which experience frequent rains or very high humidity during the flowering period. Such conditions are not conducive to good fruit set and they increase the incidence of serious diseases like powdery mildew and anthracnose (Griesbach, 2003)

1.12 Importance of Mango Crop

Mango, *M. indica* is one of the most important fruit crops in the tropical and subtropical countries in the world (Wafaa *et al.,* 2010; 2011). Worldwide, mango cultivation covers approximately 2.9 million hectares (FAO, 2001), ranking the fifth in production among major fruit crops worldwide after banana, orange, apple and coconut (IHC, 2014). Mango is among the most important fruits both locally and for the export market in Tanzania (Kimaro and Msogoya, 2012). In East Africa, the crop contributes to the earnings of nearly USD 500 million in export revenues (Griesbach, 2003). There is a great diversity of mango fruit types which permits considerable manipulation for various purposes and markets: juice, chutney, pickles, jam/jelly, fresh fruit, canned and/or dried fruit etc. Given the multiple products, it is therefore a potential source of foreign exchange for a developing country; it is also a source of employment for a considerable seasonal labour force (Griesbach, 2003).

Mango plays an important role in enabling farmers and farm workers to increase their living standards, thus contributing to sustain their livelihood and food security. Also, the sector contributes to employment opportunities to small scale producers, traders (middleman) and wholesale and retailing outlets and emerging exporters. Mango products like mango juice, mango pulp, mango flavour, mango pickles, and powder, which have been well introduced and accepted in different market segments in the world also contributes to earnings in cash income.

Currently, the sector is dominated by production of traditional varieties (Sindano; Viringe–Embe Tanga; Bongwa; Boribo, Dodo) essentially for the local market and home consumption. Introduction of new exotic varieties (Alphonso, Apple, Kesar, van dyke, Kent, Tommy Atkins etc.) have started in the last few years and are yet to bear significant results. Hence the data about production and marketing (export) especially of improved and export varieties are scattered and not complete (SCF and MMA, 2008).

1.13 Constraints in Mango Production

Production of mango fruit is threatened by several factors including irregular rainfall patterns, pests, diseases and post harvest loss during its development that result into substantial yield losses. The huge economic losses are caused by a complex of African fruit flies (FF), aggravated by a highly invasive and devastating *Bactrocera invadens* Drew, Tsurata and White (recently known as *B. dorsalis*), and the mango seed weevil, *Sternochetus mangiferae* Fabricius. Fruit flies alone have been reported to cause yield losses of between 30 – 80% in East Africa (Ekesi, 2010) depending on the locality, season and variety (Lux *et al.,* 2003a). Data on the extent of losses due to *S. Mangiferae* are not readily available in East African belt. However, losses of between 5% – 80% have been reported in India on different mango varieties (Varghese, 2000). Indirectly, *S. mangiferae* infestation stimulates the premature fall of developing fruits, spoilage of pulp, hindrance for export of fresh fruits and failure of weevil infested seeds to germinate (Varghese *et al.,* 2005). Both *S. mangiferae* and *B. dorsalis* are quarantine pests (Ekesi, 2010), thus posing serious losses in trade value and export opportunity due to strict quarantine regulations imposed by most importing countries (Kumar *et al.*, 2011). The main focus of the current study is on key mango pests mainly the fruit fly species and the mango seed weevils, *Sternochetus mangiferae*.

1.13.1 Fruit fly species

Fruit flies (FF) occupy a predominantly important place in the list of enemies of plants and among the world's most notorious agricultural pests; both because of their widespread presence and broad larval host range (Saini *et al.,* 2014). They are among key insect pest constraint for the increased and sustained production of fruit and vegetable crops in Africa (Vayssiéres *et al.*, 2008a; Ekesi *et al.*, 2009). Infestation by fruit flies has led to heavy losses in yield and quality of fresh fruits, and restrictions to quarantine sensitive markets throughout Africa (Badii *et al.,* 2015). More than 50% of the horticultural production volume is affected by fruit fly infestation (USDA-APHIS, 2008). Thus, the flies threaten production of market acceptable fruit quality (MMA, 2011).

Tephritids FF are of greatest concern owing to their extensive damage and economic losses to major fruit and vegetable crops, coupled with their quarantine status (White and Elson-Harris, 1992; Ishida *et al.*, 2005; USDA-APHIS, 2008). Sub-Saharan Africa is the aboriginal home to 915 FF species from 148 genera, out of which 299 species develop in either wild or cultivated fruit. They belong mainly to four genera: *Bactrocera, Ceratitis, Dacus,* and *Trirhithrum* (White and Elson-Harris, 1992). Most of these FF species are highly polyphagous, attacking several cultivated and wild fruits and vegetable crops (De Mayer *et al*., 2007; Rwomushana *et al*., 2008; White and Goodler, 2009).

1.13.1.1 Biology of fruit flies

Mango is usually attacked by a complex of fruit fly species. The oriental fruit fly *Bactrocera dorsalis* (Hendel) is very destructive and the dominant fruit fly species known to attack mango in the study area (Mwatawala *et al.*, 2004). This species has competitively displaced the native *C. cosyra*. The biology of *B. dorsalis* has been described by CABI, (2015). The eggs of *B. dorsalis* are laid below the skin of the host fruit. The eggs hatch within a day (although this can be delayed up to 20 days in cool conditions). Eggs hatch into larvae that feed on the decaying flesh of mango for another 6 – 35 days, depending on the season. Infested fruits quickly become inedible (Plate 1.4) or drop to the ground (Ekesi and Mohamed, 2011). Pupation occurs in the soil under the host plant for 10 – 12 days at 25^0C and 80% RH, but may be delayed for up to 90 days under cool conditions. The adults occur throughout the year and begin mating after approximately 8 – 12 days, and may live for 1 – 3 months, depending on temperature (up to 12 months in cool conditions)

Plate 1. 4 *Bactrocera dorsalis* adult (left) and Mango infested by fruit flies (right)

Sources: IAEA, 2010 (left); Abdulla *et al.*, 2012 (right)

1.13.1.2 Damage due to fruit flies

Fruit injury results from the ovipositional punctures that reduce the quality and market value of the fruit. During oviposition, fruit rottening bacteria from the intestinal flora of the fly are introduced into the fruit and cause the tissues surrounding the eggs to rot (Vayssiéres *et al*., 2009). When the eggs hatch, the rotten fruit tissues make it easier for the larvae to feed inside the fruit, resulting into soft, mushy mess (Badii *et al.,* 2015). The puncture and feeding galleries made by the developing larvae also provide entry points for pathogen infection to develop and increase in fruit decay (Kumar *et al.,* 2011). Indirect losses is associated with quarantine restrictions because infestation and sometimes mere presence of the flies in a particular country could also restrict the free trade and export of fresh horticultural produce to large lucrative markets abroad (Ole MoiYoi and Lux, 2004).

1.13.1.3 Fruit flies of importance to mangoes

Africa is the aboriginal home of several species of highly damaging FF (Badii *et al.*, 2015). For example, on mango, several survey reports across Eastern and Southern Africa (ESA) shows that the crop is attacked by native FF species such *Ceratitis cosyra* (Walker), *C. quinaria* (Bezzi), *C. fasciventris* (Bezzi), *C. rosa* (Karsch), *C. anonae* (Graham) and *C. capitata* (Wiedemann). In addition to indigenous fruit fly species, mango production in SSA is also badly threatened by the introduced exotic fruit fly species of the genera *Bactocera.* Currently, two species of *Bactrocera*, i.e. *B. zonata* Saunders and *B. dorsalis* are of importance in attacking mango

Among all the native and exotic FF species, the invasive FF, *Bactrocera dorsalis* (Diptera: Tephritidae) is thought to be responsible for causing extensive economic losses to horticultural crops throughout Africa, particularly Kenya since its first report in 2003 (Lux *et al.*, 2003b). The pest was subsequently detected in other African countries (Ekesi *et al*., 2006, 2009). Without control, direct damage has been reported to range from 30 – 80% depending on the fruit, variety, location and fruit season (Mwatawala *et al*., 2006). Studies conducted in Tanzania, where *B. dorsalis* was detected in 2003, reported losses ranging from 20% to 61.7% (Ekesi *et al*., 2006; Mwatawala *et al*., 2006); while in Ghana and Benin losses were estimated between 60% and 85% (Vayssiéres *et* *al*., 2008b; 2009). In addition to direct losses, indirect losses due to quarantine restrictions imposed by importing countries have been enormous.

1.13.1.4 Management tactics for fruit flies

Several cultural methods are used farmers in mamanging FF in their orchards. However, due to polyphagous nature of FF, suppression of their populations to lower levels is quite complicated. Most FF species are facultative breeders, i.e. they start laying eggs whenever their host fruits are available, and so they may have several generations per year (Sarwar, 2015). Besides undertaking numerous measures against the pest, but it is still disappointing to encounter eggs or maggots in the ripening fruit. Cultural measures of FF management commonly used by farmers includes male annihilation (sing Methyl Eugenol as lure), spot application of bait spray (mixture of protein hydrolysate and the insecticide Malathion), early harvesting to avoid infestations, i.e., before fruit fly attacks the fruits and good orchard hygiene to prevent fruit fly eggs and maggots from developing in infested fruit (Ekesi, 2010).

Mass trapping of FF has a potential to obtain information on the abundance and species composition of fruit flies in the field. Thus, the traps not only give an overview of whether a control measure is needed or not, but also have a potential as a tool playing an important role in disruption of the mating process. Fallen fruits left on the ground act as a major breeding site for FF (Liquido, 1991). Therefore, field sanitation through removal and destruction of old fruit remaining is important in reducing overall FF densities. For good results, to eliminate or reduce this reservoir it is important to collect and destroy all fallen fruits before, during and after fruit harvest by deep-burying (> 50 cm deep) or by feeding them to animals. Alternatively, the fruits should be sealed inside black plastic bags and exposed to direct sunlight for several hours (Ekesi, 2010).

Area wide approach is needed to reduce fly densities and level of infestation reductions of between 75% and 100% are possible if sanitary measures are applied. In managing FF, a single control method is often not sufficient to eradicate or even effectively control the fruit fly from an area (Sarwar, 2015). Insecticides are commonly used with some success. However, to ensure insecticide free fruits are harvested, it is recommended to use other robust and sustainable management tools available, such as the use of *O. longinoda*.

1.13.2 Mango seed weevil

The mango seed weevil, *Sternochetus mangifereae* (Fabricus) (Coleoptera: Curculionidae), is an important pest of mango fruits world wide (Peña *et al.*, 1998). The weevil has only one known host, cultivated and wild *Mangifera* spp (Queensland Government, 2012). The weevil produces only a single generation per annum. The development period from egg to adult is variable, depending on prevailing temperatures (Shukla and Tandon, 1985). Adults become reproductively active when mango plants begin to flower, and the females randomly oviposit on developing mango fruit (Hansen *et al.*, 1989). Small marble-size fruits are preferred, but almost fully grown fruits may also be attacked (Peña *et al.,* 1998). Generally, only a single larva completes development in each fruit, but as many as five larvae have been reported (Hansen *et al.*, 1989). Larval development occurs within the seed and only very rarely in the pulp (Plate 1.5).

Plate 1. 5 Dissected fruit showing seed damaged by *S. mangiferae* (left) and Adult *S. mangiferae* with oviposition marks on a fruit (right).

Sources: Abdulla *et al.,* 2012 (left); Peng and Christian, 2005 (right).

1.13.2.1 Biology of *S. mangiferae*

The biology of *S. mangiferae* was explained by Smith, (2008). Female weevils lay their eggs by making a shallow depression in the fruit skin. It then covers the egg with exudate and cuts a crescent-shaped slit in the skin just above the egg which causes a flow of sap to cover the immediate area. After some time, the sap dries to form a hard, amber-coloured, protective resin over the oviposition site. After five to seven days, the first instar larvae hatch from the egg and burrow through the mango flesh to the young developing seed. The immature stages of *S. mangiferae* are spent as an off-white grub and a creamy coloured pupa within the seed. The seed is often completely destroyed by the feeding activity of one, two or more larvae. After the fruit matures and falls to the ground (or is harvested), the adult weevils chew a hole through the seed covering to emerge. This can occur between 22 and 76 days after fruit drop, but averages 45 days. *S. mangiferae* may lay up to 15 eggs per day and can deposit almost 300 over a three month period.

After emergence, the weevil search for a hiding place like beneath loose barks of trees or in waste material under the trees where they remain dormant until the next flowering season (Balock and Kozuma, 1964). During the early fruit-set stage, adult weevils move to the flower panicles or, if available, soft flush leaf tissue, to feed and may be seen at night or in the early morning. They have been known to survive more than four and a half months without food and water, and 21 months when food and water are supplied.

1.13.2.2 Management tactics for *S. mangiferae*

Cultural methods of control are commonly used in managing *S. Mangiferae* (De Graaf, 2010). Thus, in order to maintain an orchard to seed weevil free status, it is important to avoid movement of fruits from areas known to have mango seed weevils to areas where young orchards, free of seed weevil, have been established (Queensland Government, 2012). A strict policy of not bringing mango fruit into the orchard will greatly reduce the chance of infestation. The biggest source of MSW infestation is dropped fruits or seeds lying around in which weevils can survive up to about 300 days. Therefore, good orchard sanitation is very important. Regular removal and destruction of fallen fruit, seeds and plant debris is very important and effective to prevent hiding of adult weevils (De Villiers, 1987; Peng and Christian, 2004). This will aid in minimizing the infestation in following seasons. Fallen fruits should be collected and destroyed by burying them to a depth of about 50 cm deep.

An attack by *Sternochetus mangiferae* can be detected by monitoring for egg-laying marks on young mango fruits. Therefore, regular fruit scouting is important to detect adult activity during fruit growth (Peng and Christian, 2007). Treatment of the trunk and branches with insecticides is very effective against MSW when timely applied. The most suitable stage to apply a spray is when the first eggs are noticed on the fruit. At this time the adults are active within the canopy, moving on the fruit and can be targeted together with the newly laid eggs. Long-lasting contact insecticides such as Azinphos, Endosulfan, Malathion, Fenthion etc. mixed with a spreader or sticker liquid are usually recommended. Insecticide applications are usually repeated at intervals of 2 – 3 weeks. Good spray coverage to run-off is critical to ensure effective control (Griesbach, 2003).

Among these management tactics, insecticides are most popularly used by farmers to suppress the weevils to reasonable lower population levels. However, they are not always effective especially when not properly timed. On the other hand, insecticides are associated with a number of drawbacks including health hazard to consumers, pesticide resistance and resurgence to insects and environmental health (Ouna *et al.,* 2010). As such a need for a more effective and sustainable control measures cannot be overemphasized.

1.14 Weaver Ants as Effective Bio-control Agents

The importance of native natural enemies became obvious after broadspectrum pesticides had swept away many of the natural enemies. Recent works on weaver ants *Oecophylla* spp. indicated ants as highly efficient pest controllers as they actively patrol canopies and prey upon or deter a wide range of potential pests (Van Mele, 2008a). It was shown that weaver ants can reduce pest numbers and their damage and increased yields in multiple crops (Van Mele, 2008a; Offenberg, 2015). Their efficiency in protecting tree crops is comparable to chemical pesticides (Offenberg, 2015). Written records indicate that *O. smaragdina* was recognised in China as a biological control agent as early as 304 AD (Van Mele, 2008a). The two *Oecophylla* species, *O. longinoda* (Latreille) (Hymenoptera: Formicidae) in Africa and *O. smaragdina* (Fabricius) in Asia and Northern Australia (Plate 1.6) have since been documented as most effective biocontrol agents of a range of insect pests.

Plate 1. 6 Asian weaver ant, *Oecophylla smaragdina* protecting queen ant (left) and the African weaver ant, *O. longinoda* nest on mango tree (right).

Sources: Moffett, 2011 (left); Mallusatish, 2011 (right).

More than 100 pest species belonging to eight orders and 26 families on eight tropical tree crops and six forest trees are controlled by *Oecophylla* ants (Peng and Christian, 2010). The biology and ecology of the two *Oecophylla* species are so similar that they can be treated as one (Peng *et al*., 2011).

Experience in South East Asia and Australia shows that weaver ants, *O. smaragdina* have been used as a major component of integrated pest management (IPM) programmes for cashew and mango since 1995 (Peng *et al*., 2011). Similarly, the African weaver ants, *O. longinoda* has been reported as effective biocontrol agents (Plate 1.7) against citrus pests (Ativor *et al*., 2012) and cashew (Dwomoh *et al*., 2009) in Ghana; coconut (Way, 1953; Varela, 1992; Seguni, 1997) and cashew in Tanzania

(Olotu *et al.,* 2012); Mozambique, (Peng, 2002) and mango in Benin (Sinzogan *et al.*, 2008; Van Mele *et al.,* 2007a, 2009a; Adandonon *et al.,* 2009; Vayssiéres *et al.,* 2013).


Plate 1. 7 *Oecophylla longinoda* attacking *P. wayi* (left) and *O. longinoda* attacking fruit fly (right)

Sources: IAEA, 2010 (left); Abdulla *et al.,* 2013 (right).

1.14.1 Biology of weaver ants

In *Oecophylla* ants, sexual intercourse occurs between males and virgin queens which conduct a mating flight (nuptial flight) after which the males quickly die and the new fertilized females attempt to establish new colonies, thus to become egg-laying queens (Hölldobler and Wilson, 1990; Van Itterbeeck *et al.,* 2014). The life cycle of the *Oecophylla* ant has four stages: egg, larva, pupa, and adult. Once mated, the queen looks for a nesting site, either on trees or open fields. She then gets rid of her wings, seals herself into a small chamber and lays a small batch of eggs (OISAT, 2015). The eggs then hatch into larvae. The queen is located in one nest and her eggs are distributed to other nests within the colony where worker ants are found. A single queen is responsible for all the reproduction needs of the colony.

The larvae feed on the unfertilized eggs as food which the queen lays especially for them. The first brood of workers is normally smaller since she can only provide a limited amount of food. Once the ants mature, they leave the nest and begin to look for preys. They bring food to the queen and their siblings so that later offspring are bigger. As the colony reaches maturity, it begins to produce the queens and males for the next generation. The developmental period for the weaver ant to complete its life cycle from an egg into an adult worker takes approximately 30 days.

Weaver ant colonies are founded by one or more mated females' egg laying queens (Peng *et al.*, 1998). A queen (Plate 1.8) lays her first clutch of eggs on a leaf and protects and feeds the larvae that develop into different castes due to various embryonic, environmental or nutritional factors (Brian, 1979). Weaver ants exhibit a clearly bimodal size distribution, with almost no overlap between the size of the minor and major workers (Hölldobler and Wilson, 1990). Workers perform tasks that are essential to colony survival, including foraging, nest construction, and colony defense. Major workers forage, defend, maintain and expand the colony, while minor workers tend to stay inside or close to the nests where they tend the brood and scale insects (Babu *et al.*, 2011).

Plate 1. 8: Weaver ant queens, *Oecophylla smaragdina* (left) and *O. longinoda* (right)

Source: IAEA, 2010.

1.14.2 Ecological requirements of weaver ants

Weaver ants (Hymenoptera: Formicidae) are arboreal and build woven leaf nests in canopies of trees and shrubs (Offenberg, 2015; Crozier *et al.*, 2010). Two species are currently known and these are *Oecophylla longinoda* Latreille, and *O. smaragdina* Fabricius, (Bolton *et al.*, 2007). In terms of habitat ranges, the African variant of the *Oecophylla* family occurs in most tropical areas of Africa while *Oecophylla smaragdina*, a keystone predator species is very abundant in any habitat with trees from Sri Lanka and India, through southern China, South-East Asia, and Melanesia to northern Australia (Cole and Jones, 1948, Way, 1954; Hölldobler and Wilson, 1990; 1994).

Their feeding behaviour is generalistic (Way 1954, Vanderplank, 1960). They are numerically dominant in natural ecosystems compared to other ant species (Bigger, 1981), and they are abundant enough to be effective in controlling pests in a wide range of tree crops (Crozier *et al.*, 2010). They comprise at least one-third of all insect biomass and may equal the biomass of humans (Hölldobler and Wilson, 2009). Colonies might cover large areas defending huge, three-dimensional territories, and one colony may occupy several trees at one time (Hölldobler and Wilson, 1990; 1994). The ants inhabit several crops such as cashew, cocoa, coffee, citrus, mango etc. (Van Mele and Cuc, 2007b).

Distribution of *Oecophylla* species is determined by two physical parameters, i.e. mean annual rainfall and average minimum temperature. Temperatures below 17 ^{0}C inhibit larval development (Lokkers, 1986). *Oecophylla smaragdina* prefers environmental temperatures between 26 and 34 ^{0}C and relative humidity between 62% and 92 % (Van Mele and Cuc, 2007a). The African weaver ant, *O. longinoda* are found in area with evergreen tree and bush vegetation (Way, 1954). In east African belt, the ants have been reported colonizing trees on areas along the coast of Kenya, Tanganyika and on the Islands of Pemba, Zanzibar and Mafia where temperature ranges between 24 and 29 ^{0}C and relative humidity of between 45% - 84 % predominates in greater part of the year (Way, 1954).

1.14.3 Augmentation and conservation of *Oecophylla* species

When using *Oecophylla* ants efficiently in pest control, it is often necessary to manage their population to high densities (Offenberg, 2015). Many strategies have been developed to reduce species loss and enhance beneficial *Oecophylla* species to flourish in agro-ecosystems in different parts of the world. The major strategies include limiting the action and suppression of competing ant species like *Pheidole megacephala*, for example, connecting trees with the same colony using an aerial artificial bridge (twisted polystrings of more than three mm in diameter or a bamboo stick) to facilitate *Oecophylla* communication and ensuring equal distribution of *Oecophylla* species between trees (Van Mele and Cuc, 2007a; Peng *et al.,* 2008), pruning trees to reduce ants fighting between neighbouring colonies (Offenberg, 2015), providing supplementary ant feeding (sugar, water and sometimes protein) during dormancy period of the host plant, limiting use of insecticides, limiting the action of competing ant species to climb and forage on plants canopies, for example by avoiding clean weeding under host trees, by applying sticky barriers around tree trunks or by chemically or physically controlling undesired species (Majer, 1986; Way and Khoo, 1992; Peng *et al.*, 2008; Seguni *et al.,* 2011) which will in turn favour the beneficial ant and its competitive ability (Seguni *et al.,* 2011). Diversity in vegetation, by intercropping and maintenance of ground vegetation was found to benefit *Oecophylla* spp. by increasing their food sources and nesting sites (Way and Khoo, 1992; Seguni *et al.,* 2011).

1.15 Weaver Ant Competitors

Competition between individuals of different species is a common phenomenon among ants. The outcome of ant competition may result in replacement of a colony, loss of brood, failure to exploit a food resource or sometimes the loss of the entire colony (Hölldobler and Wilson, 1990). Among other competing ant species, the primarily ground-nesting big-headed ant, *Pheidole megacephala* (Fabricius) that occurs throughout the tropics and subtropics are the important competitors of weaver ants in different agro-ecosystems (Vanderplank, 1960; Varela, 1992; Seguni, 1997; Sporleder and Rapp, 1998). *Pheidole megacephala* have been reported to prey on weevils and prevent them from laying eggs on sweet potatoes and banana plants, they also collect nectar, pollen and small seeds from the ground vegetation (Perfecto and Castiñeiras, 1998). *Pheidole megacephala* is highly invasive and can compete with dominant arboreal *Oecophylla* species to occupy tree crowns more readily in orchards than in rain forests because of the lower and less dense canopy in orchards (Kenne *et al.,* 2003). *Pheidole megacephala* is thus considered to be the most efficient and most widely distributed competitor of *O. longinoda* (Perfecto and Castiñeiras, 1998). When *Oecophylla* faces strong competition, it defends its territory, and consequently its effectiveness to control tree pests is reduced (Seguni *et al.,* 2011).

Therefore, in order to establish flourishing colonies of *Oecophylla*, other dominant competing ants present in the orchard have to be managed. This will result into an increase in ant densities beyond natural levels and ensure maximum pest control

(Offenberg, 2015). Thus, knowledge of plants that will favour competing ant species is important when designing agro ecosystems suitable for the survival and establishment of strong *O. longinoda* colonies (Van Mele and Chien, 2004; Van Mele, 2008b). Oswald and Rashid, (1992) achieved effective suppression of *P. megacephala* populations in coconut plantations by using Amdro® bait (hydramethylon). However, use of Amdro® bait is not acceptable in organic production systems.

1.16 Weaver Ant Limitations

Weaver ants show high potential as natural biocontrol agents. However, the technology faces the following challenges:

(i) Weaver ants protect sap feeding insects such as scale insects, mealybugs and aphids from which they collect honeydew (Tsuji *et al.,* 2004). They are known to have a mutual relationship with mealybugs and aphids. This is because the excreta of mealy bugs and aphids contain sugar, which is part of the diet of weaver ants. By protecting these insects from predators they increase their population and increase the damage they cause to trees (Blüthgen and Fiedler, 2002).

(ii) Some farmers are reluctant to use weaver ants, as they attack not only pests but also humans. Weaver ant aggression and subsequent painful bites aggravated by irritating chemicals (formic acid) secreted from their abdomen has been an obstacle for its use in many parts of the world, mainly in plantations, and therefore *Oecophylla h*as often been considered a pest (Way and Khoo, 1992). A number of ways to reduce the nuisance from ants have been reviewed by Van Mele *et al.*, (2009b). Wearing beekeeper protective clothing or the application of fine powder (e.g. cassava flour or wood ash) on hands and feet will reduce attacks from worker ants. Also, spraying of water will inactivate the ants for a while and allow a less painful during fruit harvest.

Researchers have different perceptions about weaver ants. Tsuji *et al*., (2004) who found that the presence of *O. smaragdina* in rambutan, *Nephelium lappaceum* flowers significantly decreased visiting rates of flying insects, including the major pollinator, *Trigona minangkabau* reported weaver ants to deter the beneficial organisms. In contrast, Pierre and Idris, (2013) did not find any negative effects of *O. smaragdina* on the major pollinator, *Elaeidobius kamerunicus* of oil palms, as the ants did not attack the beetles.

1.17 Justification of the Study

Cashew production in Tanzania is low and has been unstable due to a complex of sucking insect pests (NARI, 2008). Infestation by these pests can lead to 60 –100% yield losses (ICIPE, 2011). Similar to cashew, mango production is also badly affected by insect pests leading to excessively low yields. The biggest threats to mango production in East Africa are the existence of fruit flies, particularly the *B. dorsalis* Hendel, and the mango seed weevil, *S. mangiferae* Fabricius (Ekesi, 2010). Quarantine restrictions on infested fruits are severely limiting export of fruits to large lucrative markets in

European, American and Asian markets. Results of several surveys across Eastern and Southern Africa (ESA) showed that yield loss on mango due to native fruit flies range between 30 – 80% depending on the locality, variety and season (Lux *et al.*, 2003a; Mwatawala *et al.*, 2006; Ekesi *et al.*, 2009). However, since invasion of *Bactrocera dorsali*s in 2003 in East Africa, damage to mango has increased to over 80% (Ekesi *et al.*, 2009).

Cultural methods for pest management have been adopted by growers for a long time due to its environmentally friendly nature and minimal costs (Gill *et al.*, 2013). On mangoes for example, several methods such as field sanitation have been used in reducing population of both FF and the MSW with good success, but effective only when practiced on a wider area and not on spotted areas. Similarly, spot application of bait spray can successfully be used to suppress FF population to lower levels. However, in managing cashew and mango insect pests, insecticide sprays have been the most common crop protection practices with some success. Although insecticides work effectively in suppressing the pest populations, the main concerns about repeated pesticide use are their toxicity and negative impacts on the health of farmers and workers handling and applying them, consumers as well as the environment (Christos and Ilias, 2011; Bhandari, 2014; Egonyu *et al.*, 2014; Peng *et al.*, 2014). Also, many of the chemical-based control options are costly and often associated with resurgence of the insect pests (Ouna *et al.*, 2010). Thus, more effective and environmental sound pest management alternative that will guarantee sustainable production of mango need to be developed (Sarwar, 2015).

Studies in South East Asia and Australia have shown that *O. smaragdina* has been successfully used as a biological control agent of insect pests in cashew and mango in Vietnam; similar observations were reported in Australia (Peng *et al*., 2011). However, only few studies have been reported on the predatory abilities of *O. longinoda*, the counterpart in Africa (Sinzogan *et al*., 2008). It would therefore important to determine the biocontrol activity of the less exploited *O. longinoda* for its potential use in IPM in African cropping systems. *Oecophylla longinoda* occur in large numbers on cashew, mango and other plants in Tanzania, yet very little is known and relatively few entomologists have studied them in a pest management context. Moreover, no studies have been reported on the effect of ant feeding on their predatory efficiency. Therefore, a study focusing on the possibility of using *O. longinoda* in an IPM in cashew and mango orchards is of utmost importance.

1.18 Objectives

1.18.1 Overall objective

The overall objective of this study was to contribute to increased yields of cashew and mango through a natural enemy-based pest management option for major insect pests.

1.18.2 Specific objectives

The overall objective was addressed through the following specific objectives: -

(i) To compare the effectiveness of *O. longinoda* Latreille (Hymenoptera: Formicidae) versus insecticide on major cashew insect pests.

(ii) To determine the effect of supplementary feeding of *Oecophylla longinoda* on their abundance and predatory activities on cashew pests.

(iii) To determine the effectiveness of *O. longinoda* Latreille (Hymenoptera: Formicidae) in controlling key mango insect pests.

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CHAPTER TWO

2.0 POTENTIAL OF *OECOPHYLLA LONGINODA* LATREILLE (HYMENOPTERA: FORMICIDAE) IN MANAGING MAJOR INSECT PESTS IN ORGANIC CASHEW PRODUCTION SYSTEMS

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2.1 Abstract

Cashew production in Tanzania is severely constrained by sucking insect pests such as the coreid coconut bugs (*Pseudotheraptus wayi* Brown), the mirid bugs, *Helopeltis* spp and Thrips spp. These pests damage flushing foliar and floral shoots as well as young cashew fruits and nuts. Farmers rely heavily on insecticides to control these pests and there are no suitable alternative control methods compatible with organic cashew production. Weaver ants, *Oecophylla longinoda* Latreille have for long been considered as effective biological control agents against sap-sucking pests of cashew but studies on their effectiveness as compared to conventional insecticides had never been conducted. The current study evaluated the efficiency of *O. longinoda* as compared to the recommended conventional insecticide, lambda cyhalothrin (Karate®) in controlling major cashew insect pests and compared the resulting cashew yield. The damage caused by each pest was significantly lower (P<0.0001) on trees with weaver ants and in the plots treated with Karate® than was the case on the control trees. There were no significant differences (P>0.05) in the damage between *O. longinoda* and Karate® treated trees suggesting that the two treatments are equally effective. Yield increases of 58.2% and 60.7% in the insecticide treated trees and in the *O. longinoda* protected trees, respectively were obtained, in relation to untreated control plots during the two seasons. Thus, *O. longinoda* can serve as an alternative to chemical insecticides for protection of cashew in Tanzania.

Keywords

Cashew, lambda-cyhalothrin, Naliendele, *Oecophylla longinoda*, organic production, sucking insect pests

2.2 Introduction

Cashew (*Anacardium occidentale* Linnaeus) is the main cash crop and the leading source of income for over 300,000 households in south-eastern Tanzania. About 40 million cashew trees are grown on an estimated 400,000 ha of land (NARI 2008). Cashew is attacked by a number of insects particularly thrips, *Selenothrips rubrocinctus* Giard, the coreid coconut bug, *Pseudotheraptus wayi* (Brown) and mirid bugs, *Helopeltis anacardii* Miller and *Helopeltisschoutedeni* Reuter. These insects suck and feed on new tender shoots, flower panicles, and young developing fruits (NARI 2010). The insects also attack leaf and floral flushing shoots causing cause early abortion of young nuts and substantial loss of yields (Igboekwe 1985; Azam-Ali and Judge 2006). There is no single technique that has been found to be effective in the management of these pests. Currently, cashew farmers use several synthetic pesticides to control the pest populations. However, most of these pesticides have adverse impacts on farm environment and farmers' health (Peng et al. 2014). Synthetic pesticides affect non-target species, resulting in the development of insect resistance and resurgence (Saini et al. 2014). In order to make cashew production environmentally safe, sustainable and profitable, alternative natural methods of pest management had to be explored. If such measures become effective, they would minimize the risk of using synthetic chemical insecticides and as a result meeting the requirement of organic farming (Oruanye and Okrikata 2010).

Experience from South East Asia shows that the weaver ant, *Oecophylla smaragdina* (Fabricius), has been successfully used for centuries as a predator and repellent of a range of arthropods, including over 80 species of insect pests on 11 crops and four forest trees in 14 countries (Peng et al. 2008). Weaver ants have also been known to improve the quality of fruits, like mango and citrus (Van Mele 2008), as well as nuts of cashew (Peng et al. 2008). The use of weaver ants increased the net profits to mango and cashew growers in Northern Territory of Australia (Peng and Christian 2008). Several studies have reported a significant reduction in pest damage by *O. smaragdina* in for example citrus plantations in Vietnam (Van Mele and Cuc 2007), mangoes in Australia (Peng and Christian 2005), and cashew orchards in Australia and Vietnam (Peng et al. 2011). Ants as tools in sustainable agriculture have also been reviewed by Offenberg, (2015).

Insecticides are widely used to control sap sucking insect pests of cashew in Tanzania. Safer alternatives to insecticides are desirable, but these can only be accepted by farmers based on evidence from comparable field studies. The Asian weaver ant, *Oecophylla smaragdina* Fabricius (Hymenoptera: Formicidae), which is closely related to *O. longinoda*, has been used successfully as biological control agents against a number of pests in different agricultural systems in South East Asian countries and Australia (Offenberg, 2015). Conversely, majority of reported works on *Oecophylla* research do not compare the ant technology with the prevalent conventional pest control methods (Offenberg et al. 2013). Reports from works done in cashew plantations in Ghana (Dwomoh et al. 2009), Tanzania (Olotu et al. 2012) and Benin (Anato et al. 2015), suggest that *O. longinoda* can effectively control sap-sucking pests in cashew. However, the previous studies in Tanzania did not include any commercial insecticide and were limited to damage assessment. Studies in Benin explored effects of *O. longinoda* and spot application of GF 120 (Spinosad 0.02%) on yield and quality of cashew. None of these studies included conventional insecticide sprays. Furthermore, the previous studies did not combine yield and damage assessment. Farmers who would like to adopt organic cashew production would require comparable yield and damage between conventional insecticides and *O. longinoda* technology, before making sound decisions. It was necessary to explore this information to facilitate adoption of *O. longinoda* technology by cashew farmers in Tanzania.

If effective, the use of weaver ants could offer an alternative control method, and help African farmers to avoid toxic pesticides, which are expensive, not always available when needed and not friendly to the environment. This paper aimed at evaluating the efficiency of weaver ants in controlling major cashew insect pests in organically produced cashew in Southern Tanzania.

2.3 Materials and Methods

2.3.1 Experimental set up

Experiments were conducted for two consecutive cashew seasons (2012/13 and 2013/14) at Naliendele Agricultural Research Institute (NARI) in Mtwara, Tanzania (S10^0 20' 55.69"; 040^0 10' 04.11" E 120 masl). The experiments were undertaken in a plot measuring 324 m x 196 m, with 10-year old cashew trees planted at a spacing of 12 x 12 m. Within this plot, 216 trees of cashew variety "AC4" of similar size were selected. The trees were divided into three plots of 72 trees each, separated by three rows of trees (about 36 m) that served as guard rows. Of the three plots, one was colonized by weaver ants (organic cashew plot) and another was treated with a conventional insecticide, Karate® (i.e. conventional cashew plot). The third plot was the untreated control.

2.3.2 Sulphur sprays

All trees were prophylactically protected against powdery mildew by spraying sulphur (falcon dust) fortnightly at a rate of 250 g $tree^{-1}$(Olotu et al. 2013) and in accordance to Sijaona (1997) and Smith et al. (2008). Sulphur dust has no detrimental effects on the abundance of *O. longinoda* and it is accepted in organic production systems (Olotu et al. 2013).

2.3.3 Weaver ants establishment in organic cashew plots

A total of 16 weaver ant colonies were transplanted from nearby habitats into organic cashew trees according to the procedures described by Peng et al. (2008). Each colony was distributed to 4 – 6 trees depending on size. Each tree received between six to twelve weaver ant nests. Canopies of trees occupied by the same *O. longinoda* colony were connected with nylon strings (4 mm thick in diameter) to ease ant colonisation and migration. Branches of trees occupied by different colonies were pruned to avoid contacts and subsequent ant fights (Peng et al. 2008). The bases of the tree trunks were smeared with sticky barriers to deter antagonistic soil nesting *Pheidole megacephala* Fabricius (Seguni et al. 2011) accessing the trees. Sticky barriers were regularly checked and refreshed whenever necessary. The transfer of *O. longinoda* colonies to the experimental plots was done six months before the start of monitoring the abundance of ants and pest damage. However due to attacks by *P. megacephala*, additional fifteen *O. longinoda* colonies were transferred during the experiment to replace the weak colonies. All the trees in the control blocks were regularly examined to ensure that none was colonized by *O. longinoda*.

2.3.4 Insecticide sprays in conventional cashew plots

Insecticide Karate® (50 grams/L of lambda-cyhalothrin) was sprayed at the recommended rate of 5ml/litre per tree (NARI 2010). Spraying started at the first flush of new leaves, and continued through flowering and stopped at about mid-nut development, that is, from the fourth week of July to the fourth week of September, each season. Karate® was applied four times each season, at three weeks intervals (NARI 2008), using a motorized backpack sprayer (M 225-20 Motor-Rückensprühgerät). Spraying was done late in the evening when the wind speed was low. In addition, a systemic fungicide Bayfidan, (triadimenol 250 g litre-^{1}) was applied at three-week intervals to control powdery mildew disease (PMD), (*Oidium anacardii* Noack) (Martin et al. 1997). Bayfidan was only applied in the insecticide treatment three times during the cashew fruiting season.

2.3.5 Control treatment

Trees in this treatment were only dusted with sulphur for protection against powdery mildew disease.

2.3.6 Damage assessment

Individual trees were repeatedly assessed for damage six times in each season. Lesions caused by different pests were monitored on newly flushed shoots, flowers and fruits at two-week intervals throughout the fruiting season. During each date of pest damage assessment, a 1 m^2 quadrat was randomly placed in each of the four cardinal directions of a tree´s canopy. The total number of shoots and the number of shoots damaged by each pest in each quadrat were counted. The proportions (incidences) of damaged shoots, flowers, or fruits due to each pest were then compared among treatments.

We recorded damage by *P. wayi* by examining plants for elongated, blackened, and sunken lesions on young developing shoots, fruits and spots on nuts. We also examined and recorded the damage by *Helopeltis* spp. as deformed leaves on developing shoots, plus angular black lesions and necrotic areas on tender stems, fruits and developing nuts. Thrips damage was assessed based on the observed scorched areas on leaf tissues, developing fruits and nuts. We found that under moderately or severe cases of attack by thrips, one or two longitudinal cracks appear on apples. Generally, the damages caused by the sucking insect pests were differentiated using procedures described by Peng et al. (2008).

2.3.7 Cashew yield

Yields of individual trees were assessed by counting and weighing fully ripened nuts collected under the canopy. The ground under the canopies was kept free of weeds throughout the fruiting season (from late August to late November). The collection of nuts started from late August and continued to late November in both seasons.

2.3.8 Data analysis

The data on damage caused by each of the sucking insect pests were Arcsine transformed before the analysis. To make valid inferences and to draw meaningful conclusions on the equality of means on the effect of treatments on damage was tested by using repeated measures ANOVA (done independently for each season). Bonferroni multiple tests were used to compare the treatments. Nested ANOVA was used for comparison to determine whether means cashew yield differ among the treatments. . The yield was tested separately for each season. The JMP (version 11.1.1) statistical discovery (SAS Institute Inc., Cary, North Carolina) was used for all the analyses. All statistical tests for significance were performed at $P \leq 0.05$.

2.4 Results

2.4.1 Effects of treatments on damage by *P. wayi*

The damage inflicted by *P. wayi* on unprotected trees increased from early August and reached a peak in mid-September, but declined towards the end of the fruiting season.

On the other hand, the damage decreased progressively with time in the protected cashew trees (Figure 2.1).

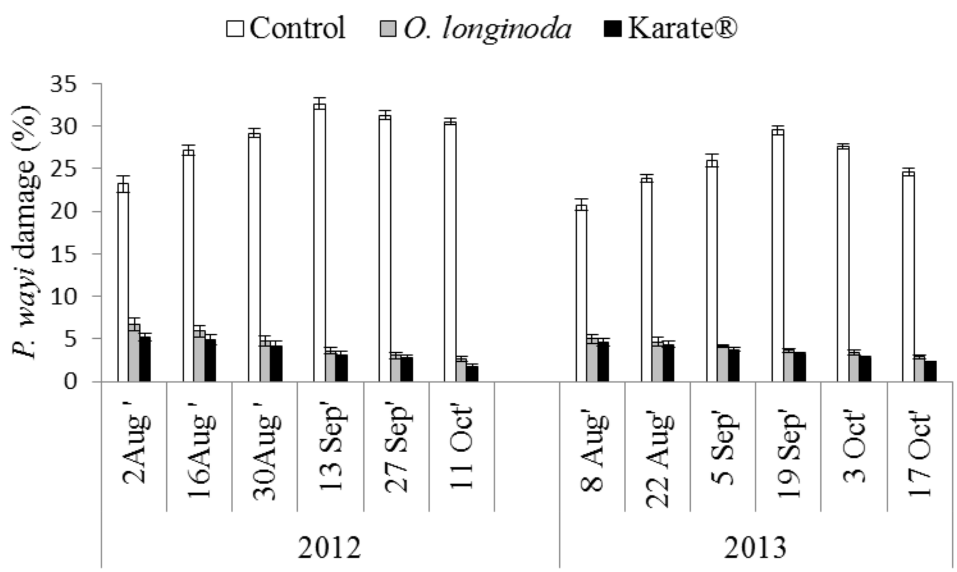

Figure 2. 1 The mean (±SE) flushing shoots, flowers and fruits damaged by *P. wayi* in different treatments during the two fruiting seasons (2012/13 and 2013/14) at NARI.

The damage caused by *P. wayi* in 2012/13 varied significantly among treatments ($F_{2, 425}$= 4094.16; *P*<0.0001), time ($F_{5, 426}$ = 3.44; *P*=0.0046) and treatment x time (Wilk's lambda test$F_{10, 850}$= 20.85; *P*<0.0001. Similarly in 2013/14, significant variations in the damage by *P. wayi* were recorded among treatments ($F_{2, 425}$ = 3878.1; *P*<0.0001), time ($F_{5, 426}$ = 11.32; *P*<0.0001) and time x treatment (Wilk's lambda test$F_{10, 850}$ = 16.63; *P*<0.0001). The damage was significantly higher in the control than was the case to organic and conventional plots, throughout the study period. The damage varied slightly but not significantly among trees in the organic and conventional plots (Table 2.1).

Table 2. 1: Bonferroni multiple comparison tests of different treatments on *P. wayi* damage for the two cropping seasons at Naliendele

	P values					
Paired treatments	Interval (weeks)					
2012/13	2	4	6	8	10	12
Control vs weaver ants	***	***	***	***	***	***
Control vs Karate	***	***	***	***	***	***
Weaver ants vs Karate	ns	ns	ns	ns	ns	ns
2013/14						
Control vs weaver ants	***	***	***	***	***	***
Control vs Karate	***	***	***	***	***	***
Weaver ants vs Karate	ns	ns	ns	ns	ns	ns

ns = not significant at p<0.05; *** P<0.001

The overall damage for both seasons was 27.22% in the control, 3.57% in Karate® and 4.20% in the organic plots. Compared to the control treatment, the damage caused by *P. wayi* was less by 87% and 86% in the conventional and less by 83% and 85% in organic plots in 2012/13 and 2013/14, respectively.

2.4.2 Effects of treatments on damage by *Helopeltis* spp.

The damage caused by *Helopeltis* species showed a trend similar to that of *P. wayi*, although at lower levels (Figure 2.2).

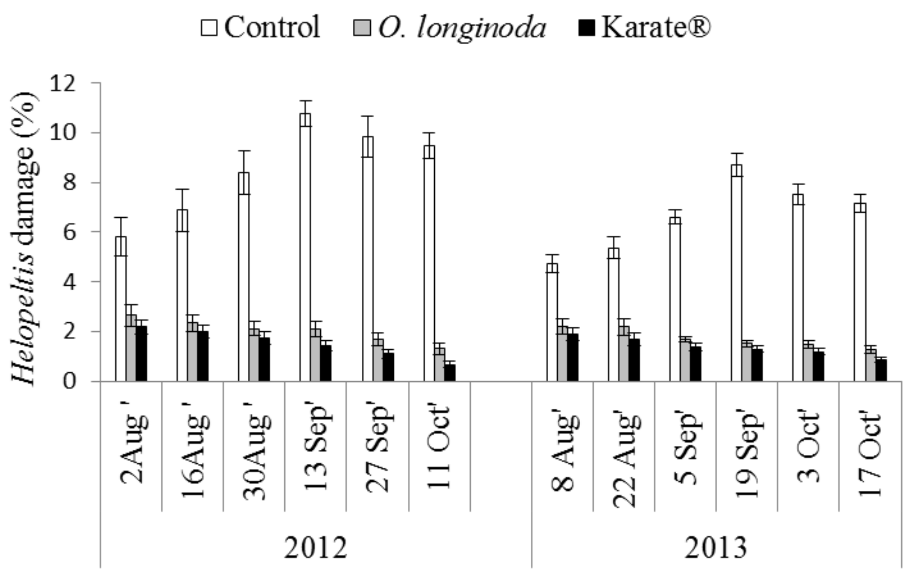

Figure 2.2 The mean (±SE) flushing shoots, flowers and fruits damaged by *Helopeltis* species in different treatments during the two fruiting seasons (2012/13 and 2013/14) at NARI.

Organic and conventional cashew suffered significantly less damage than the control trees during both 2012/13 ($F_{2, 425}$ = 253.75; P<0.0001) and 2013/14 ($F_{2,425}$ = 459.267; P<0.0001) seasons. Similarly, variations in the damage were significant over time ($F_{5, 426}$ = 2.38; P = 0.0376 and $F_{5, 426}$ =3.8; P<0.0022) in both 2012/13 and 2013/14 respectively. The interactions between time and treatment had a significant effect on the damage during both 2012/ 13 and 2013/14 seasons (Wilk's lambda test$F_{10, 850}$ =4.61; P<0.0001, and $F_{10,\ 850}$ = 8.67; *P*<0.0001 for 2012/13 and 2013/14 respectively). However, there were no significant differences in the damage among trees in the organic and conventional cashew plots during both years (Table 2.2).

Table 2. 2 Bonferroni multiple comparison tests of different treatments on damage by *Helopeltis* spp for the two cropping seasons at Naliendele

	P values					
Paired treatments	Interval (weeks)					
2012/13	2	4	6	8	10	12
Control vs weaver ants	*	***	***	***	***	***
Control vs Karate	**	***	***	***	***	***
Weaver ants vs Karate	ns	ns	ns	ns	ns	ns
2013/14						
Control vs weaver ants	**	**	***	***	***	***
Control vs Karate	**	**	***	***	***	***
Weaver ants vs Karate	ns	ns	ns	ns	ns	ns

ns = not significant at p < 0.05; *** P<0.001; **: p<0.01; *:p<0.05

The overall damage recorded during both seasons was 7.60% in the control, 1.44% in the conventional, and 1.88% in the organic cashew trees. When compared to the control, the damage caused by *Helopeltis* spp was less by 82% and 79% in the conventional and 76% and 74% in the organic cashew trees, in 2012/13 and 2013/14 respectively.

2.4.3 Effects of treatments on damage by *S. rubrocinctus*

Our results indicated higher and increasing damage by *S. rubrocinctus* in the control trees over time, during both seasons (Figure 2.3).

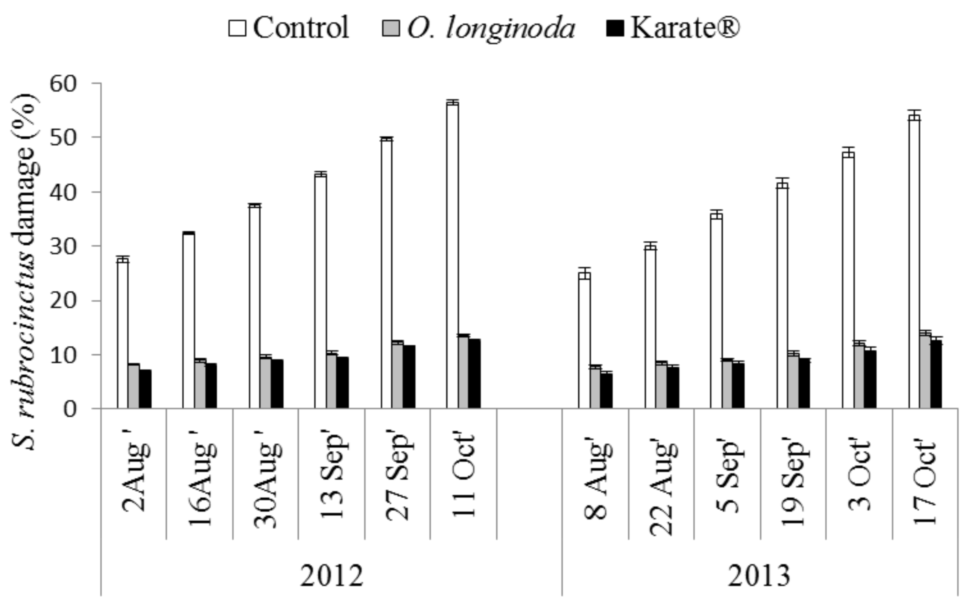

Figure 2.3 The mean (±SE) flushing shoots, flowers and fruits damaged by *S. rubrocinctus* in different treatments during the two fruiting seasons (2012/13 and 2013/14) at NARI.

Thrips damage was significantly lower in the conventional and organic than in the control trees in 2012/13 ($F_{2,425}$ = 14962.33; P<0.0001) and 2013/14 ($F_{2,\ 425}$ = 2790.55;

P<0.0001). The variations were similarly significant over time during both 2012/13 and 2014 seasons ($F_{5, 426}$ = 740.01; *P*<0.0001and $F_{5, 426}$ = 184.37; *P*<0.0001for 2012/13 and 2013/14 respectively). Time x treatment was also significant (Wilk's lambda test$F_{10, 850}$ = 116.5; *P*<0.0001and $F_{10, 850}$ = 33.89; P<0.0001) during 2012/13 and 2013/14 seasons respectively. The differences in damage among trees in organic and conventional plots were not significant (Table 2.3).

Table 2.3: Bonferroni multiple comparison tests of different treatments on *S. rubrocinctus* damage for the two cropping seasons at Naliendele

	P values					
Paired treatments	Interval (weeks)					
2012/13	2	4	6	8	10	12
Control vs weaver ants	***	***	***	***	***	***
Control vs Karate	***	***	***	***	***	***
Weaver ants vs Karate	ns	ns	ns	ns	ns	ns
2013/14						
Control vs weaver ants	***	***	***	***	***	***
Control vs Karate	***	***	***	***	***	***
Weaver ants vs Karate	ns	ns	ns	ns	ns	ns

ns = not significant at P<0.05; *** P<0.001

The overall recorded damage by *S. rubrocinctus* in both years was 40.06% in the control, 9.39% in the conventional and 10.71% in the organic cashew. Compared to the control treatment, the damage caused by *S. rubrocinctus* was less by 87 and 86% in the conventional and in the organic cashew trees; and less by 75 and 73% in 2012/13 and 2013/14 seasons respectively.

2.4.4 Cashew yield

The average yield of raw cashew nuts (kg^{-1} tree) for the two years/seasons was 2.83±0.14SE in the control, 4.54±0.19SE in the *O. longinoda* and 4.47±0.18SE in Karate® treatments (Figure 2.4).

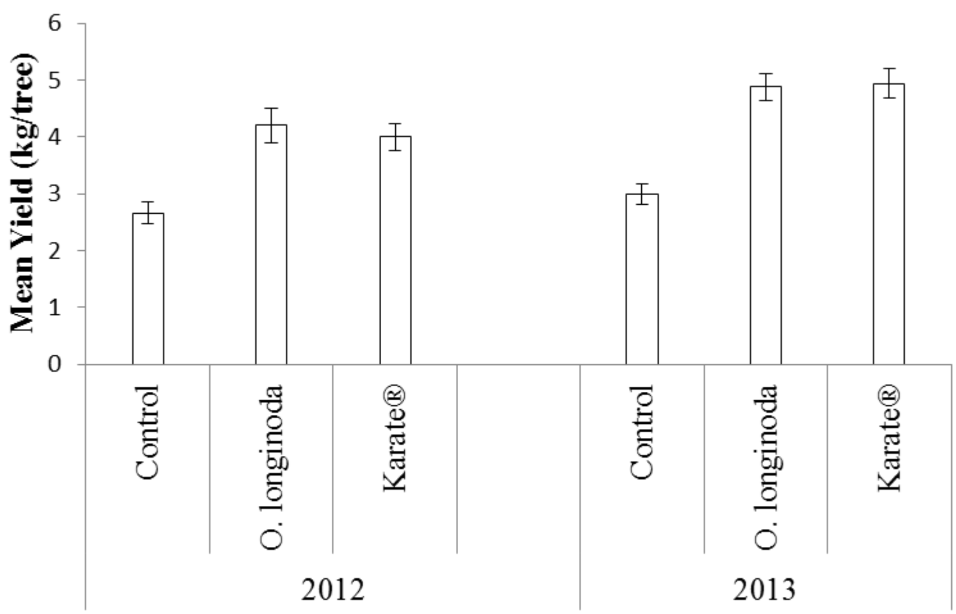

Figure 2. 4: **Mean (±SE) raw nut yields per tree (kg/tree) in different treatments in the two consecutive cashew cropping seasons (2012/13 and 2013/14) at Naliendele Agricultural Research Institute in Tanzania.**

Trees in the conventional and organic plots produced significantly higher yields than those produced in the control trees in 2012/ 13 and 2013/14 ($F_{2,70}$ = 13.66; P<0.0001and $F_{2,70}$ = 34.67; *P*<0.0001). However, there was no significant difference between the former two treatments.

Proportionate differences in the yields between treatments were lower than the differences in pest damage. Compared to the control, conventional cashew recorded higher yields by 50% and 65%; whereas in the organic cashew, the yields recorded were higher by 58% and 63% in the 2012/13 and 2013/14 seasons respectively.

2.5 Discussion

Our results showed that *O. longinoda* is an effective biocontrol agent against major cashew sucking insect pests in an organic cashew production system. Similarly, the application of insecticides at recommended rate and frequency of four times in a season proved to be effective in conventional systems. Both *O. longinoda* and insecticide application protected cashew against sucking insect pests with *O. longinoda* being as effective as the currently recommended conventional insecticide, Karate®.

High damage by sucking pests started to increase at the beginning of the fruiting seasons, when tender flushes of young shoots, inflorescences, panicles, developing young nuts and apples were available. Similar results were reported previously (NARI 2010; Olotu et al. 2012; Maruthadurai et al. 2012). The commencement of the fruiting season usually coincided with the availability of a wider range of food resources necessary for survival, reproduction and population build up in insect pests.

We observed consistently less damage in the organic cashew trees protected by *O. longinoda* compared to the control trees throughout the two seasons (2012/13 and 2013/14), which corroborate to a report by Olotu et al. (2012). Previous studies showed that several crop species benefitted from the predatory abilities of weaver ants; these included palms (Sporleder and Rapp 1998; Pierre and Idris 2013), mango (Van Mele et al. 2007; Offenberg et al. 2013; Abdulla et al. 2015), citrus (Van Mele et al. 2002), and African mahogany (Peng et al. 2010), among others. Many researchers have reviewed *Oecophylla* ants as effective biological control agents (Van Mele, 2008; Way and Khoo, 1992; Peng and Christian, 2004; and Offenberg, 2015).

Our results further showed that, for both seasons, the average damage by *P. wayi* was as low as 3.57% and 4.54% in the conventional and organic cashew trees as opposed to 27.22% in the control. Similarly, the recorded damage by *Helopeltis* species was 1.44% and 1.87% in the conventional and organic cashew trees respectively, as opposed to 7.6% in the untreated control. These findings confirmed the effectiveness of *O. longinoda*as a biocontrol agent against both *P. wayi* and *Helopeltis* species and validated the previously reported findings by Olotu et al (2012) that *O. longinoda* can effectively control cashew sucking insect pests. Based on our results, it is evident that *O. longinoda* was as effective against cashew insect pests as the currently recommended insecticide, Karate®. Similar findings were reported by Peng et al. (2008); Van Mele (2008) and Dwomoh et al. (2009).

On average, the damage by *S. rubrocinctus*in *O. longinoda* protected tress was as low as 10.72% compared to over 40% damage in the unprotected trees. However, in Benin cashew damage increased when trees were attended by *O. longinoda*, although, the ant protected trees still produced up to 122% higher yields than the yields produced in the control trees (Anato *et al.* 2015). Weaver ants control may be integrated with compatible methods when lower damage levels are desired. Peng and Christian (2005) for example, integrated *O. smaragdina* with Neem, *Azidarachta indica* Juss and in this way successfully reduced thrips damage in mango. As biocontrol agents, weaver ants prey on any insect venturing into their territory, consequently reducing the damage on flushing shoots and developing nuts (Varela 1992; Seguni 1997; Pierre and Idris 2013).

We recorded higher yield from the protected than from the unprotected trees. Trees colonized by *O. longinoda* gave similar yields to those protected by Karate®. However, the application of weaver ant technology is generally cheaper than the application of insecticides (Peng and Christian 2005; Offenberg and Wiwatwitaya 2010; William et al. 2015; Offenberg 2015) and compatible with organic production systems, whose products fetch higher prices (Ramesh et al. 2010; EPOPA 2004). A study by William et al. (2015) showed that the net benefits of controlling insect pests were higher when using weaver ants than when using insecticides. Furthermore, the weaver ants technology is affordable to most resource poor farmers and also applicable in mixed cropping systems often used by such farmers. We recorded higher yields in the 2013 than we did in the 2012 season partly due to availability and distribution of rainfall. Southern Tanzania received reliable rainfall during the 2013 as opposed to 2012 season. The application of Sulphur to control powdery mildew disease was timely available and sprayed in the 2013 as opposed to the 2012 season. Furthermore, conventional cashew benefitted from additional sprays of Bayfidan (triadimenol 250 EC, Bayer Crop Science) to suppress powdery mildew disease. We also recorded frequent attacks of *O. longinoda* by competitor ants, *P. megacephala* during the 2012 season, thus affecting predatory efficacy of the former.

Insecticides on the other hand, can be hazardous to human and environmental health (Egonyu et al. 2014), and unacceptable levels of residues in exported products may be a barrier to international trade (Fianko et al. 2011). There are also risks of resistance and resurgence related to use insecticides in agriculture (Saini et al. 2014).

2.6 Conclusion

Oecopphylla longinoda may serve as reliable biocontrol agents in organic cashew production in Tanzania. The ants have a high future potential, considering a worldwide increasing demand for organic products and sustainable pest management strategies.

The African weaver ant, *Oecophylla longinoda* occurs naturally in many tropical areas in the country and the results of the present study can be expanded to other regions through (i) coordinated long-term experiments, including networks of spatial-temporal extensive multifactor experiments, in collaboration with ecologists, modelers and social scientists (ii) creating farm networks and demonstration plots that are managed by extension agents and farmers with limited involvement of researchers and (iii) conducting awareness campaigns using various forms of mass media (iv) increasing access to *O. longinoda* colonies by perfecting techniques for obtaining fertilized queens of *O. longinoda* through trapping (Rwegasira et al. 2015) and rearing of ant queens in nurseries (Ouagoussounon et al. 2015).

2.7 Future studies

Future studies should consider a number of factors that may have contributed to errors in the present study. These included sporadic attacks by competitor ants *P. megacephala*, incidences of powdery mildew disease, non-uniformity in sizes of cashew trees, and non uniformity in sizes of transplanted *O. longinoda* colonies.

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CHAPTER THREE

3.0 EFFECT OF SUPPLEMENTARY FEEDING OF *OECOPHYLLA LONGINODA* ON THEIR ABUNDANCE AND PREDATORY ACTIVITIES AGAINST CASHEW INSECT PESTS

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3.1 Abstract

Many studies have shown the efficiency of using weaver ants (*Oecophylla* species) as natural bio-control agents against agricultural pests. Supplementary feeding could promote fast growth of this ant's population and discourage them from moving away.

However, such artificial feeding might slow down ant´s search rates and in this way make them less efficient bio-agents. The experiments were conducted for two consecutive seasons at Naliendele Reseach Station. Cashew trees planted at a spacing of 12 m x 12 m in 2002 were used to investigate whether supplementary feeding could enhance foraging behaviour of *O. longinoda*. Fed *O. longinoda* colonies (FWA) were supplemented with a 30% sugar solution and approximately 22 g of finely ground fish meat at two-week intervals while the un-fed colonies (UWA) had access to only naturally occurring food sources. Weaver ant densities and pest damage was monitored fortnightly on newly damaged shoots, panicles and fruits and nut yields assessed after each harvest season. The results revealed that there was a significant difference ($P<0.05$) with higher weaver ant densities in the FWA compared to UWA colonies and significantly lower ($P<0.05$) pest damage levels were recorded on weaver ant treatments compared to plots without weaver ants. No significant differences ($P>0.05$) in yields and mean damage levels were recorded between the two weaver ant treatments. Highest nut yields (4.22 ± 0.30kg/tree and 5.37 ± 0.27kg/tree) were recorded in the fed colonies, followed by non-fed colonies (4.20 ± 0.30kg/tree and 4.88 ± 0.24kg/tree) and the least (2.66 ± 0.19kg/tree and 2.99 ± 0.19kg/tree) was recorded from the untreated controls in 2012/13 and 2013/14, respectively. The studies indicated that supplementary feeding could boost weaver ants to higher population levels without reducing their effectiveness as biocontrol agents.

Keywords: Ant feeding, biocontrol agents, *O. longinoda*, predatory activities, supplementary feeding.

3.2 Introduction

Weaver ants (*Oecophylla* spp.) are among the earliest recorded biological control agents. They are considered as one of the most effective groups of predacious ants against insect pests (Way & Khoo, 1992, Van Mele, 2008). *Oecophylla* spp. is effective in controlling over 50 species of insect pests on many tropical tree crops (Peng & Christian, 2013). The positive effect of these ants has been described in many studies, and efforts have been put forward to develop techniques to improve their use in biological control (Peng, Christian, & Gibb, 2004; Van Mele, 2008). It has been demonstrated that the presence of ant pheromones may be sufficient to repel pest insects (Adandonon, Vayssières, Sinzogan, & Van Mele, 2009; Van Mele, Cuc, Seguni, Camara, & Offenberg, 2009) from ant territories and the pheromones may serve an important role in the attraction of symbionts that may be essential for efficient plant protection (Offenberg, 2014).

Weaver ant biocontrol is based on predation and foraging of trees by major workers (Van Mele, Vayssières, Tellingen, & Vrolijks, 2007). The workers target potential prey and are aggressive towards large intruders that threaten their territory (Way & Khoo, 1992; Peng & Christian, 2005). Further indirect control may be achieved via olfactory and visual cues (Offenberg, Nielsen, MacIntosh, Havanon, & Aksornkoae, 2004; Van

Mele, Cuc, Seguni, Camara, & Offenberg, 2009; Adandonon, Vayssières, Sinzogana, & Van Mele, 2009; Vayssières, Sinzogan, Adandonon, Van Mele, & Korie, 2013).

Apart from being utilized for biological control, *Oecophylla* ant larvae are a commercial product in several Asian countries where they are used as edible protein for human consumption or for feeding birds (Offenberg & Wiwatwitaya, 2010). Using *O. longinoda* as a biocontrol agent or for protein production is both ecologically sound and inexpensive if the ants can be found in the surrounding habitats as ant colonies need only little external inputs to function, and as ant farming only requires simple management techniques. Further, the ants may be simultaneously utilized for plant production (biocontrol) and protein production in a particular plantation as the two services are compatible (Offenberg & Wiwatwitaya, 2010). In all cases to be effective in controlling insect pests or to produce protein on horticultural and tree crops, it is important to maintain the ant populations at high densities (Peng & Christian, 2005; Offenberg & Wiwatwitaya, 2010). In a two year study, Olotu, du Plessis, Seguni, & Maniania, (2012) showed reduced damage by sap sucking insect pests on cashew in Tanzania when *O. longinoda* were abundant. Similar observations were recorded on coconuts in East Africa (Varela, 1992), and on cashew in West Africa (Dwomoh, Afun, Ackonor, & Agene, 2009; Anato, Wargui, Sinzogan, Offenberg, Adandonon, Vayssières, Kossou, 2015) and on mango in Tanzania (Materu, Seguni, & Ngereza, 2014).

Number of individuals in an ant colony can increase rapidly depending on the availability of food under natural conditions (Van Mele & Cuc, 2007). Farmers are known to use waste products, such as chicken intestines to attract ants and in this way keep them more evenly distributed in their orchards (Van Mele & Cuc, 2007). Therefore, supplementing weaver ants with sugar and protein sources may promote their growth and ensure that high, stable and strong ant colonies are maintained to control insect pests at the onset of the fruiting season (Peng, Christian, Lan, & Binh, 2008b). Feeding the ants may also potentially reduce the effort of the weaver ants to search for prey (Van Mele & Cuc, 2007). To determine if ant feeding results in higher ant densities and is compatible with biological control, the present study explored whether supplementary feeding of *O. longinoda* could promote ant abundance and if feeding affected the ant´s efficacy as biocontrol agents.

3.3 Materials and Methods

3.3.1 Experimental set up

Experiments were conducted during the 2012/13 and 2013/14 cashew cropping seasons at Naliendele Agricultural Research Institute, Mtwara Region, southern Tanzania (040^0 10' 04.11" E 10^0 20' 55.69" S, 131m. above sea level). Ten year old cashew trees, variety AC4 of similar age, canopy size and appearance were chosen for the study. A field measuring 288 m x 180 m was divided into three blocks of (i) trees with fed weaver ants (FWA) (ii) trees with unfed weaver ants (UWA) and (iii) control trees without ants. Each treatment contained 72 trees that were assessed fortnightly for damage by the coreid coconut bug, *Pseudotheraptus wayi* Brown; the tea mosquito bugs, *Helopeltis anacardii* Miller and *H. schoutedeni* Reuter and thrips species, *Selenothrips rubrocinctus* Giard which is the dominant species in the study area.

3.3.2 Introduction of weaver ant colonies

Ant colonies were collected from nearby villages and transplanted into cashew trees. The colonies were harvested after identifying the nest containing the maternal egg-laying queen (Peng, Christian, Lan, & Binh, 2008b). Nests of different colonies were excluded to avoid ant competition. The nests were placed in marked plastic bags and transported to the orchard where they were opened and hung on lower branches of cashew trees, mostly under the shade. A total of 16 colonies were transplanted into each of the two weaver ant treatments. Each colony received between 50 – 80 ant nests and was given access to 4 – 6 trees, depending on colony size. All ant colonies were supplied with sugar solution, drinking water and finely ground fish meat during the first week of their establishment. Trees occupied by the same weaver ant colony were connected with nylon ropes (>3mm thick in diametre) to facilitate ant movements for foraging non foraged trees. Overlapping canopies of trees with two different weaver ant colonies were pruned to avoid contacts and ant competition. A gap of 1 metre was maintained between trees occupied by different colonies. This was done in accordance to procedures described by Peng & Christian, (2005).

3.3.3 Application of sulphur dusting against Powdery Mildew Diseases (PMD)

Sulphur (falcon dust) was applied at the rate of 250 g $tree^{-1}$ for the control of PMD. This disease which is associated with the fungus *Oidium anacardii* Noack, is among the major constraints in Tanzanian cashew production (Intini & Sijaona, 1983; Waller, Nathaniels, Sijaona, & Shomari, 1992). The disease has become an annual epidemic in all cashew cultivars planted in Tanzania (Martin, Topper, Bashiru, Boma, De Waal, Harries, Kasuga, Katanila, Kikoka, Lamboll, Maddison, Majule, Masawe, Millanzi, Nathaniels, Shomari, Sijaona, & Stathers, 1997; Sijaona, Clewer, Maddison, & Mansfield, 2001). An attack by PMD can cause a yield loss of between 70–100% depending on the phytosanitary measures (Sijaona & Shomari, 1987; Shomari, 1996). The flowers buds, young developing nuts, leaves and shoots of untreated trees are attacked by PMD, resulting in poor harvest and inferior nut quality (Shomari, 1996; Sijaona, Clewer, Maddison, & Mansfield, 2001). Sulphur applications started at the onset of panicle growth, and continued throughout the flowering period, at 14-days intervals (Sijaona, 1997). This was applied using a motorized sprayer.

3.3.4 Supplementary feeding

Supplementary feeding started on the third week of July (i.e. two weeks before the onset of data collection) and was repeated at intervals of two weeks. On each feeding date, wet ground fish was placed on at least three feeding stations in each colony. One spoonful (approximately 22 g) of wet, finely ground fish was placed on the tree branches two metres above the ground. One sugar feeder was placed on each tree in a colony following procedures described by Peng, Christian, Lan, & Binh, (2008b). Sugar solution (0.35g/ml) was offered in 15 ml test tubes plugged with cotton wool and placed upside down on a twig, approximately two metres above the ground (Offenberg & Wiwatwitaya, 2010). Sticky barriers (15 – 20 cm broad bands) were applied at the base of the tree trunks to prevent competition with soil nesting ants *Pheidole megacephala* Fabricius and *Anoplolepis custodiens* Smith that can be detrimental to weaver ant foraging (Seguni, Way, & Van Mele, 2011). Sugar was available ad libitum as feeders were not depleted between feedings whereas finely ground fish meat was removed within two days after feeding.

3.3.5 Abundance of *O. longinoda*

The abundance of *O. longinoda* was estimated fortnightly using branch method developed by Peng & Christian, (2005). Assessments were conducted between 15h30 and 17h30 when weaver ants are most active during this period. Dejean, (1990) reported that *O. longinoda* is continuously active with a greater number of individuals present between 9h: 00 and 17h: 00 than other times of day, but no period of low activity is found at the hottest time of the day. The ant abundance on each tree was expressed as a percentage per tree by taking a proportion of the number of main branches with active weaver ant trails on a tree to total number of main branches of the tree multiplied by 100 as described by (Peng & Christian, 2005).

The number of ant nests per tree was also counted and recorded in situ. A stepladder was used where it was difficult to observe nests from the ground e.g. due very large and dense canopy. Nest numbers have been documented to be negatively correlated to pest damage in cashew crops in Ghana, (Dwomoh, Afun, Ackonor, & Agene, 2009); Tanzania (Olotu, du Plessis, Seguni, & Maniania, 2012) and mango fruit fly damages in Benin, (Van Mele, Vayssières, Tellingen, & Vrolijks, 2007). For this reason, methods of boosting *Oecophylla* nests in an orchard is gaining momentum in crops like cashew, mango, citrus, coffee, cocoa and coconut (Van Mele, 2008).

3.3.6 Assessment of pest damage

Lesions caused by sap sucking insect pests (*P. wayi*, *Helopeltis* spp. and *S. rubrocinctus*) were monitored on newly flushed shoots, flowers and fruits within a 1 m^2 quadrat randomly positioned in four geographical positions of the tree canopy (N, E, W and S). The assessment was done from August to October in 2012/13 and 2013/14 at two-week intervals. Damage caused by each of the three sucking insect pests was differentiated based on the observed symptoms. Damage by *P. wayi* is characterized by elongated, blackened and sunken lesions that later becomes depressed hard swellings, and scars of fruit plus spots on kernels. Deformed leaves with angular black lesions, plus necrotic areas on tender stems, fruits and developing nuts indicated damage by *Helopeltis* species. Scorched areas on leaf tissues, developing fruits and nuts indicated damage by *S. rubrocinctus*. Under moderately or severe attack by *S. rubrocinctus*, one or two longitudinal cracks appears on apples (Peng, Christian, Lan, & Binh, 2008a). The proportion of damaged shoots, flowers or fruits for every individual pest was then calculated into percentage by taking the number of damaged shoots to total number of shoots assessed from one square metre quadrat multiplied by 100 as per Peng & Christian, (2005).

3.3.7 Determination of nut yields

Total nut yields per tree was assessed for each of the two years (2012/13 and 2013/14) fruiting seasons. This was undertaken by scouring the area under each tree canopy and collecting the nuts. For the nuts to be easily traced, the area under the trees was kept free from weeds throughout the harvesting season, i.e. from August to December. For every tree the weight of the collected nuts was recorded for comparison between treatments.

3.3.8 Data analysis

The effect of treatments for each group of pest species was compared for each fruiting season by a Kruskal-Wallis non-parametric test on the median followed by a pairwise two-sided multiple comparison analysis using the Dwass, Steel, Critchlow-Fligner (DSCF) method (Dwass, 1960; Steel, 1960; Critchlow and Fligner, 1991). The mean yields for each season was compared between treatments by non-multiple comparison test using Wilcoxon method after test for homogeneity of variance and arcsine transformation. The SAS Institute Statistical Package (version 9.3) was used with all statistical tests performed at $P \leq 0.05$ level of significance.

3.4 Results

3.4.1 Abundance of *O. longinoda*

Results of this study showed that the population of ants was higher in the FWA compared to the UWA blocks for both seasons (P≤0.0001). Supplementary feeding resulted in an increase in ant abundance by 27% in 2012/13 and of 11% in 2013/14. Ant abundance increased as the season progressed, during both seasons. However the population dropped towards end of the 2012 fruiting season following a strong *P. megacephala* attack in the orchard (Figure 3.1).

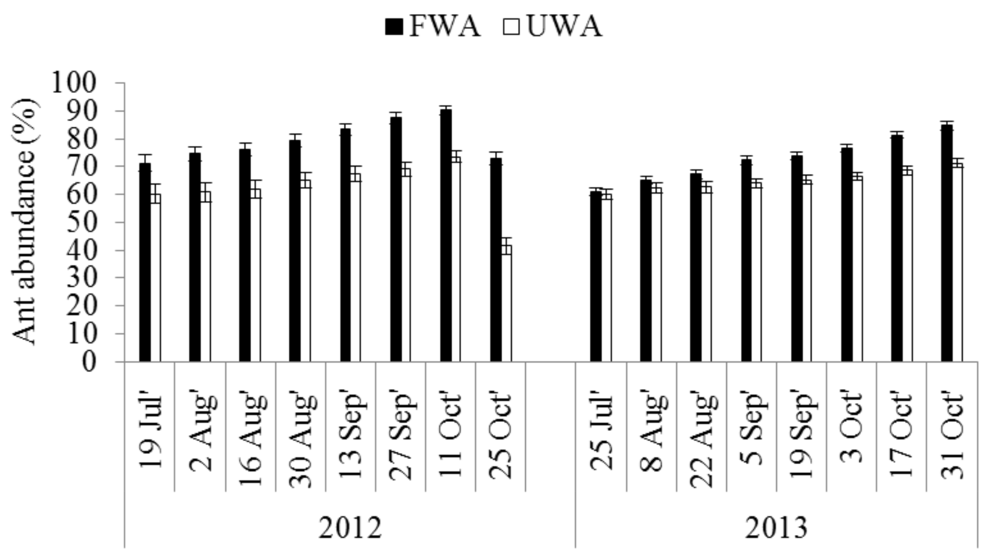

Figure 3.1: *Oecophylla. longinoda* abundance assessed via Peng 1 branch method. Bars show mean values (±SE) by date for trees with and without ant feeding during two fruiting seasons at Naliendele.

Supplementary feeding resulted into increased mean *O. longinoda* abundance from 71.18% to 90.22% in FWA, while the abundance of *O. longinoda* increased from 60.12% to 73.55% in UWA. This suggested higher ant abundance and population build up could be achieved when the ants are supplemented with sugar and protein food sources.

Likewise, there were more nests in plots of fed compared to unfed *O. longinoda.* An overall increase in the number of nests by 45% in 2012/13 and an increase of 34% in 2013/14 (P<0.0001) were recorded. Number of nests increased during each season, but declined towards the end of 2012 following *P. megacephala* outbreak in the orchard. Further, the difference in number of nests between FWA and UWA increased with the progress of the season in each year (Figure 3.2).

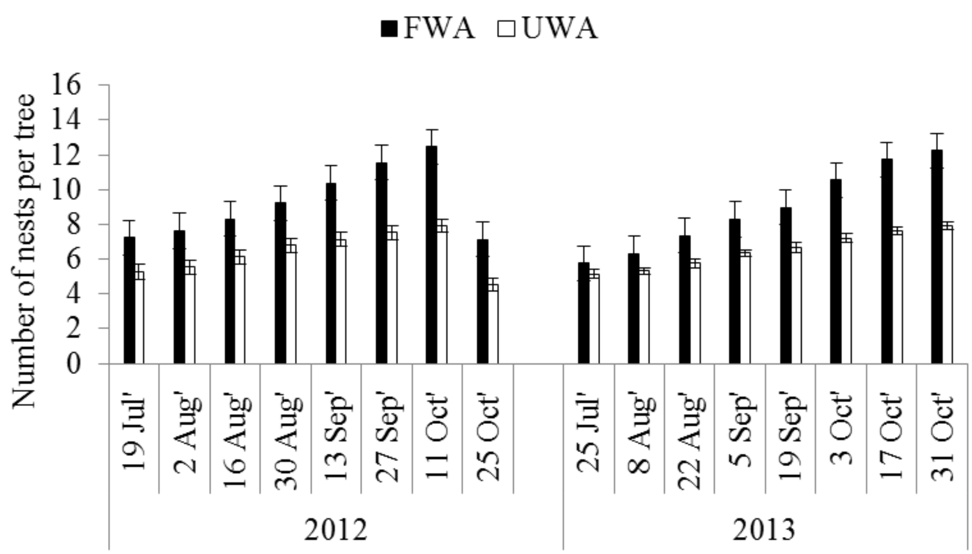

Figure 3. 2 Average number of ant nests per tree (±SE) by date in treatments with and without ant feeding during two fruiting seasons at Naliendele.

3.4.2 Pest damage

3.4.2.1 *P. wayi* damage

Damage due to *P. wayi* was significantly lower on ant protected trees compared to the control trees (P< 0.0001). However, no significant difference (P=0.21) in damage was recorded between plots with the fed and the unfed ants (Table 3.1).

Table 3. 1: Pairwise statistical comparisons of treatments on damage caused by different pests on cashew at Naliendele in Mtwara using non parametric multiple comparisons (DSCF).

Treatments	Pest	*P*-value 2012	*P*-value 2013
	P. wayi		
UWA vs FWA		0.4199^{ns}	0.1512^{ns}
UWA vs Control		$<0.0001^{***}$	$<0.0001^{***}$
FWA vs Control		$<0.0001^{***}$	$<0.0001^{***}$
	Helopeltis spp		
UWA vs FWA		0.3538^{ns}	0.1975^{ns}
UWA vs Control		$<0.0001^{***}$	$<0.0001^{***}$
FWA vs Control		$<0.0001^{***}$	$<0.0001^{***}$
	S. rubrocinctus		
UWA vs FWA		0.062^{ns}	0.279^{ns}
UWA vs Control		$<0.0001^{***}$	$<0.0001^{***}$
FWA vs Control		$<0.0001^{***}$	$<0.0001^{***}$

ns = not significant at P≤ 0.05

Generally, damage by *P. wayi* was less by 84 and 85 % in 2012/13 and 2013/14 respectively (Figure 3.3) (i.e. when results from FWA and UWA are pooled and compared to control).

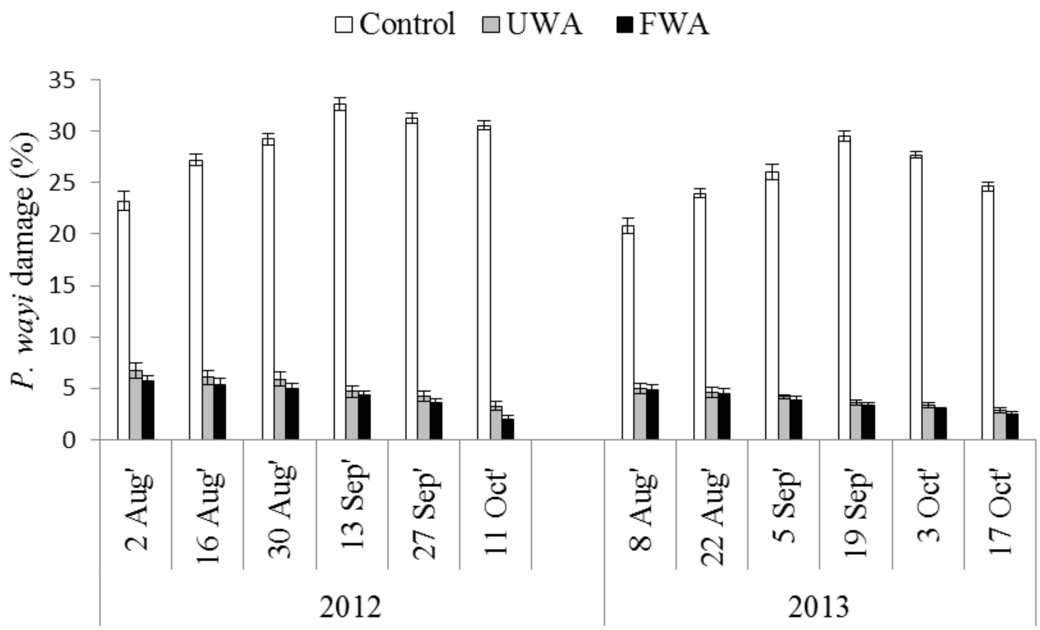

Figure 3. 3: *Pseudotheraptus wayi* damage on flushing shoots, flower panicles and fruits as a function of treatments during two fruiting seasons at Naliendele. Bars show the mean (±SE) percentage of damage.

3.4.2.2 Damage by *Helopeltis* species

Feeding did not significantly ($P = 0.25$) affect damage caused by *Helopeltis* spp. (Figure 3.4). However, damage was significantly higher in the control treatment compared to the two ant treatments ($P<0.0001$). Generally, damage by *Helopeltis* spp. in the weaver ant protected plots was less by 78 and 76% in 2012/13 and 2013/14, respectively, compared to the control (i.e. when results from FWA and UWA were pooled and compared to control).

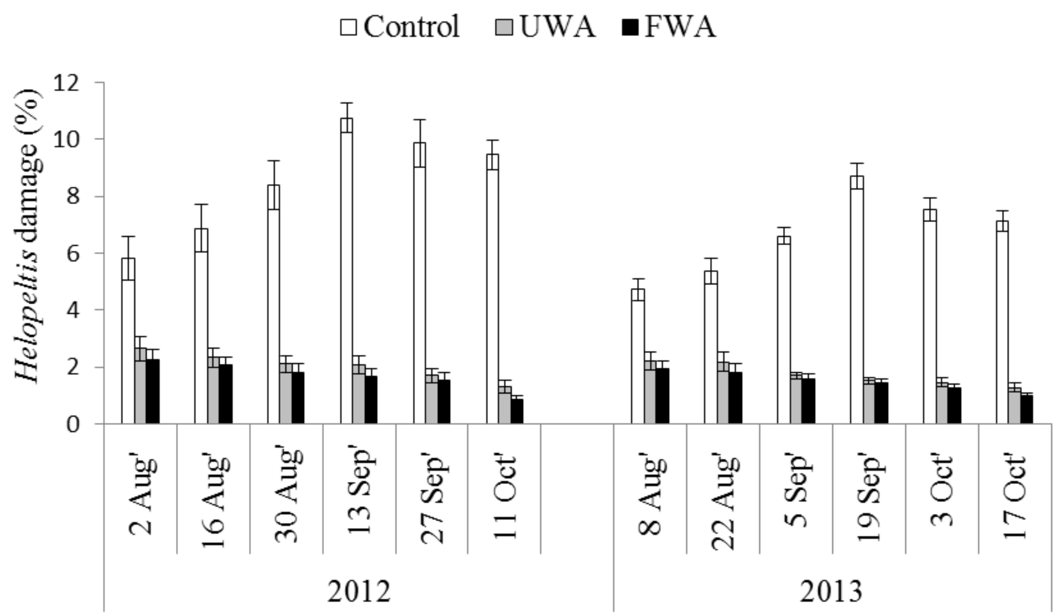

Figure 3. 4: *Helopeltis* damage on flushing shoots, flower panicles and fruits as a function of treatments during two fruiting seasons at Naliendele. Bars show the mean (±SE) percentage of damage.

3.4.2.3 Damage by *S. rubrocinctus*

Damage was significantly low (P<0.0001) on trees protected by weaver ants compared to the control plots (Figure 3.5). The damage by *S. rubrocinctus* was less by 75% and 73% in 2012/13 and 2013/14, respectively due to the presence of weaver ants compared to the control plots. However, there was no significant difference (P= 0.23) in damage between trees colonized with fed and unfed weaver ants.

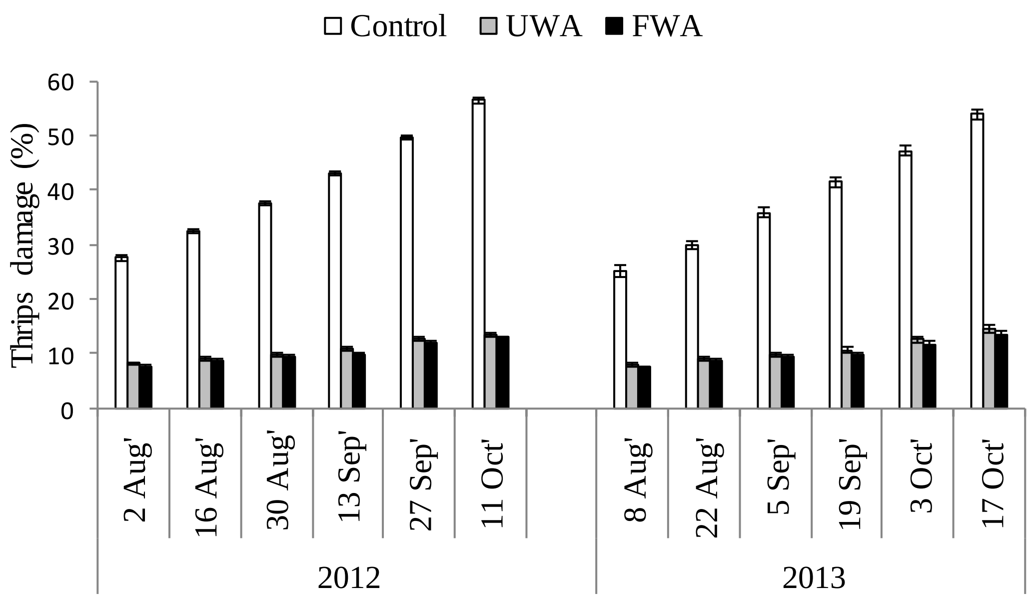

Figure 3. 5: **Percent damage due to *S. rubrocinctus* in the FWA; UWA protected trees and the control plots at Naliendele. Bars show the mean (±SE) percentage of damage.**

3.5 Nut Yields

For both two years, the yields in weaver ant treatments were not significantly different (P=0.5828) while significant differences were found between the control and the weaver ant treatments (Table 3.2).

Table 3. 2: Pairwise statistical comparisons of treatments on cashew yields at Naliendele, Mtwara using non parametric multiple comparisons (DSCF).

Treatments	*P*-value 2012	*P*-value 2013
FWA vs Control	< 0.0002***	< 0.0001***
UWA vs Control	<0.0002***	<0.0001***
UWA vs FWA	0.992ns	0.2943ns

ns = not significant at P≤ 0.05

Overall, slightly lower yields were recorded in 2012/13 compared to 2013/14. During both seasons, the highest nut yields were recorded in the fed weaver ants followed by the unfed ant treatment. Lowest yields were recorded in the control trees (Figure 3.6).

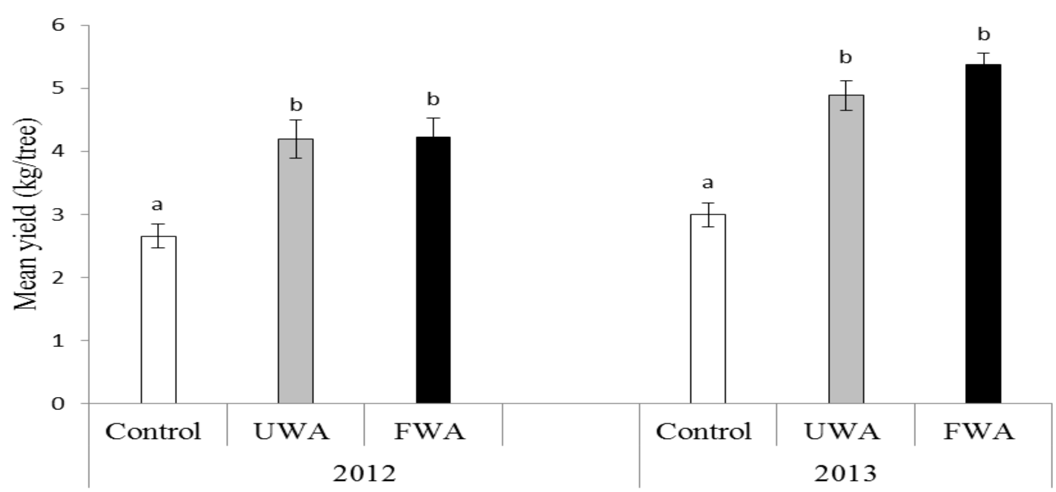

Figure 3. 6: **Mean nut yields (kg/tree) recorded from trees protected by the weaver ants (FWA + UWA) and the control plots at Naliendele during two fruiting seasons. Bar charts marked with different letters for each year indicate that the yields are statistically significant (Dwass, Steel, Critchlow-Fligner method).**

The yields were higher by 59% and 71% in the weaver ant plots compared to control in 2012/13 and 2013/14 respectively, when the results of ant treatments were pooled and compared to the control.

3.6 Discussion

It is clear from the present results that *O. longinoda* attendance led to reduced pest damage and increased yields. It is also evident that provision of supplementary food leads to higher ant abundance. However, the resulting increase in ant abundance did not increase *O. longinoda* predation of insect pests nor did it translate into significantly increased yields.

Previous studies have shown that the presence of *O. longinoda* reduces pest damage in cashew plantations. Reduced damage and increased yields have been reported by Dwomoh, Ackonor, & Agene, (2009); Olotu, du Plessis, Seguni, & Maniania, (2012) and Anato, Wargui, Sinzogan, Offenberg, Adandonon, Vayssières, Kossou, (2015). These authors observed negative correlations between ant abundance and pest damage in cashew in Ghana; Tanzania and Benin, respectively. Dwomoh, Ackonor, & Agene, (2009), further, showed a positive correlation between ant abundance and yields. Supplementary feeding could promote biological control since high weaver ant densities are linked to increased protection of the colonized tree crops. However, in the present study such effect was not detected. The reason could be that the abundance of ants was high, (>50%) in both ant treatments regardless of feeding. Adequate protection was achieved without feeding the ants while feeding did not significantly affect damage levels and yields. Among other factors, yield is also related to the level of insect pest attack, variety, and farm maintenance. The present study supports claims that adequate protection by *O. longinoda* is achieved when more than 50% of trees in a plantation are occupied by ants (Peng & Christian, 2005; Peng, Christian, Lan, & Binh, 2008a). This was the case in both ant treatments, except periods towards the end of the first season, when *O. longinoda* was attacked by *P. megacephala*.

Ant feeding did not affect yields in the present study thus the investment in feeding was not economical. Feeding was thus futile on a short term. However, ant feeding may benefit farmers in the long term if such activity leads to more stable and persistent *O. longinoda* populations. Stable populations mean fewer replacements of weak or dying colonies. Colony replacement is labour intensive (Offenberg, Nguyen, Cuc, & Wiwatwitaya, 2013), and fewer replacements means ants are constantly present providing continuous protection of the crop. *Oecophylla. longinoda* is known to compete fiercely with *P. megacephala*, which reduces the efficiency of the weaver ants as bio-agents (Seguni, Way, & Van Mele, 2011). Feeding may sustain population of *O. longinoda* during and after attacks by *P. megacephala* and other competitors. In the current study for example, ant abundance (based on Peng's branch method) declined much less in the FWA compared to the UWA treatment after attacks by *Pheidole* ants. Thus, the satiated *O. longinoda* colonies may have been better at withstanding the attacks and competition from *Pheidole*. Generally, a strong colony defends its territory and usually takes much longer time to be outcompeted by *P. megacephala*, unlike non-fed colonies (N. R. Abdulla, unpublished data). Also, ant feeding may be beneficial in cases where ant densities are lower. Feeding may raise ant abundance beyond the (established) critical low level needed for achieving adequate protection (Peng & Christian, 2005; Peng, Christian, Lan, & Binh, 2008a). Such feeding may be especially important when cashew trees are dormant. During this period trees do not produce extra-floral nectar to attract a wide range of insects and usually support lower numbers of homopterans that can produce honeydew for ants. In mono-crop systems, ants have limited opportunity to move to non-dormant host trees of different species further limiting access to nectaries and alternate prey.

Supplementary feeding during tree dormancy may then secure a high ant density at the onset of the flushing, flowering and fruiting season. This is the period when protection is mostly needed because the flowers and young nuts are always attractive to a number of insect pests (Peng, Christian, Lan, & Binh, 2008a).

It has been suggested that artificial supply of food may reduce search rate of prey by ants. As a result, ants may be less active in capturing pest insects. This claim is not supported by the present study since both pest damage and yields were not affected by feeding. The possible explanation for the observed scenario is that the ant queen under conditions with plethora of food will increase egg-laying (Ouagoussounon, Offenberg, Sinzogan, Adandonon, Kossou, & Vayssières, 2015). Once this limit is attained, feeding will no longer lead to more workers but to sexuals.

3.7 Conclusion

We conclude that *O. longinoda* was an effective biological control agent of cashew sap sucking insect pests when maintained at high and stable population levels. Moreover, feeding *O. longinoda* does not compromise their predatory abilities as was previously perceived. On the other hand, ant feeding may not lead to immediate effects on yield but may have long lasting positive effects as the *O. longinoda* may become less vulnerable to competition with other ants.

3.8 Acknowledgements

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CHAPTER FOUR

4.0 CONTROL OF MANGO SEED WEEVILS *(STERNOCHETUS MANGIFERAE)* USING THE AFRICAN WEAVER ANT *OECOPHYLLA LONGINODA* LATREILLE (HYMENOPTERA: FORMICIDAE)

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4.1 Abstract

The mango seed weevil, *Sternochetus mangiferae* (Fabricius), is among the major threats to mango production in Tanzania. *Sternochetus mangiferae* is primarily a quarantine pest whose presence inside the fruits restricts access to new foreign markets and leads to rejections of fruits destined for export. Management options for the pest have largely been dependent on field sanitation and application of synthetic insecticides with some success. Thus, more sustainable methods are needed to substitute insecticides, as this may also open up opportunities for organic markets. We conducted field experiments for two fruiting seasons in a mango plantation at Mlandizi, Kibaha district along the coastal belt of Tanzania to evaluate and compare the effectiveness of the predaceous ant *Oecophylla longinoda* Latreille with foliar insecticidal sprays of Dudumida (70 WDG Imidacloprid) in controlling *S. mangiferae*. Mango seed weevil infestation was assessed fortnightly based on infestation marks on developing fruits starting eight weeks after fruit set to early ripening phase. Between 50 and 64 fruits were sampled, well labelled in jute bags, secured and transported to the laboratory at Kibaha Biological Control Unit (KBCU) for incubation at room temperature using rearing transparent containers. Two weeks later, the fruits were dissected and inspected for presence of *S. mangiferae* developmental stages. Field and laboratory results indicated that fruits from trees that were occupied by *O. longinoda* and from those treated with insecticide showed significantly ($P<0.0001$) lower incidences and infestation rates by *S. mangiferae* than untreated trees. Furthermore, there were no significant differences between the insecticide and the weaver ant treatments. We conclude that in our experiments *O. longinoda* is an efficient biological control agent for a long term control programme and comparable to insecticide (Dudumida) in suppressing *S. mangiferae* and may be used in Tanzanian mango plantations.

Keywords Dudumida, insecticides, *Sternochetus mangiferae,* quarantine regulations, weaver ant.

4.2 Introduction

The mango seed weevil, *Sternochetus mangiferae* (Fabricius), is an important monophagous pest that seriously limits mango production worldwide (Peng and Christian 2007) and is among the most damaging insect pests of mangoes all over Africa (Joubert et al. 2000). It is a quarantine pest and its presence in export mango can lead shipments being rejected to prevent the pest's entry into countries free from the pest (Yahia 2006; Hossain et al. 2011).

Infested seeds have low germination thus hindering development of rootstock (Smith and Brown 2008). Early attack by *S. mangiferae* leads to premature fruit drop (Grové et al. 2007). *Sternochetus mangiferae* diapauses under loose bark on mango tree trunks and in branch terminals, or in crevices near mango trees during non-fruiting periods (Peng and Christian 2004). Adult *S. mangiferae* female prefers to lay eggs on median-sized or full-sized unripen fruits under the peel (Hansen et al. 1989). After hatching, the young larvae penetrate the fruit and eat their way to the seed where they feed and develop into adult weevils. Adults emerge from the seed cotyledons by tunnelling outwards through the pulp and skin of the fruit, leaving a patch where rotting soon sets in (Griesbach 2003). Losses due to *S. mangiferae* vary between 5% and 80% in different mango varieties (Varghese 2000) and infestation may stimulate premature fall of developing fruits (Varghese et al. 2005).

Insecticides and orchard sanitation have been recommended for many years (Chin et al. 2002). In conventional production systems, use of long-lasting contact insecticides such as Azinphos, Endosulfan, Malathion and Fenthion at the beginning of the mango flowering season has resulted in reduced pest damages (Griesbach 2003). However, use of insecticides is linked to high costs, reduced abundance of natural enemies, risk of pesticide residues on the fruits and environmental pollution (Peng and Christian 2007).

In South East Asia the weaver ant, *Oecophylla smaragdina* (Fabricius), is effective in controlling the main insect pests in citrus, cashew and mango orchards (Van Mele 2008), including *S. mangiferae*, (Peng and Christian 2007). In Africa, *O. longinoda* could potentially be exploited to offer control of *S. mangiferae*. However, information on predation abilities and effectiveness of *O. longinoda* on *S. mangiferae* is little documented. The current study aimed at investigating whether *O. longinoda* can control *S. mangiferae* in Tanzanian mango production.

4.3 Materials and Methods

4.3.1 Study location and set up of experiments

The studies were carried out in a mango orchard at Mlandizi, in the Coast Region of Tanzania (S 06.73468^0, 038.78356^{0}E and 98 metres above sea level). The area is characterized by bi-modal rain pattern with a short rainy season (*Vuli*) starting from November to early-January and a long rainy season (*Masika*) starting from mid-March to end of May. The mean annual temperature is 25º C and the mean annual rainfall is 1023 mm.

The experiment was conducted in a 240 x 180m block of 6 years old mango trees of the variety "Apple". Trees were 3.5 – 4 metres in height and planted at a spacing of 10 by 10 m between and within rows. The experimental block was divided into three plots of (i) trees protected by *O. longinoda* (ii) trees protected by insecticide, Dudumida (70WDG Imidacloprid) and (iii) unprotected trees (control). Each treatment comprised 72 trees in 2012/13 and 63 trees in 2013/14. A buffer zone of two tree rows was maintained between treatments. The experiment was replicated for two seasons, from August to November in 2012/13 and from October to January in 2013/14.

4.3.2 Treatments

The weaver ant treatment was achieved by introducing weaver ant colonies from a citrus orchard located about seven kilometres from the experimental plots where a maternal egg-laying queen nest was identified. Every nest in this area was collected and then introduced into the mango plantation while ensuring that all the nests belonged to the same colony as described by Peng et al. (2008a). A preliminary survey confirmed that *O. longinoda* was absent in the experimental orchard probably due to abundant *Pheidole megacephala* Fabricius, which is a competitor of *O. longinoda* (Seguni et al. 2011). To protect the introduced colonies, *P. megacephala* was suppressed by using 20 ml GF 120® (0.02% spinosad) mixed with 90 ml finely ground fish and 40 ml water. Sticky barriers were also established at the base of the mango trees to prevent *P. megacephala* and other competing ants from climbing up the mango trees to forage.

Sixteen queen-right *O. longinoda* colonies were then transplanted into the ant treatment in the experimental mango orchard. The source colonies were mapped and marked, and the nests with the maternal queens were identified before harvesting and transplanting ant nests as per Peng and Christian (2005). The colonies were transplanted six months before the start of the mango fruiting season. The six months period is deemed sufficient for ants to establish stable colonies that can effectively protect a crop. We placed 6 – 12 nests per tree and allowed each colony access to 4 – 6 mango trees (according to colony size) by connecting trees with 4 mm diameter nylon ropes to facilitate ant communication within the colony.

The newly transplanted *O. longinoda* colonies were offered a 30% sugar solution in 15 ml test tubes plugged with cotton wool and hung in the trees. The ants were also offered with approximately 22g of either cat food, finely ground fish or meat during the first week of introduction as per Peng et al. (2008a). One sugar feeder was offered on each tree in a colony and three feeding stations per colony following procedures described by Peng et al. (2008b). Cat food and water were also offered fortnightly during the dry season (May – July) when mango trees were dormant and food was scarce. Water was offered in 500ml plastic bottles with a small twig into the bottle to make easier for the ants to access the water without falling.

In the insecticide, Dudumida (70WDG Imidacloprid) was applied at a rate of 10ml/tree (as per manufacturer's recommendations) using hand operated back-pack sprayer every three weeks from the onset of flowering until a month before harvesting. In the control treatment, trees were left without any insect control measures. However, all experimental trees were sprayed with potassium nitrate applied at the rate of 10 g/tree to induce uniform flowering of the trees. Trees were also protected from powdery mildew, *Oidium mangiferae* Berthet, by spraying Megasin–M 70WP (70% Thiophanate methyl) at the rate of 100 g/tree based on manufacturer's recommendations.

4.3.3 Assessment of *S. mangiferae* on developing mango fruits

Assessment of damage symptoms caused by *S. mangiferae* was done fortnightly on $1m^2$ quadrats randomly positioned on each of four poles of the tree canopy on 72 and 63 mango trees in each treatment during 2012/13 and 2013/14 fruiting seasons respectively. This was done from the fourth week of August until fifth week of October in 2012 and from first week of October to third week of December in 2013. In each quadrat the number of shoots with developing fruits, and the number of shoots bearing fruits with oviposition marks by *S. mangiferae* were recorded ensuring that none of the damaged shoot is counted twice. A pocket-magnifying lens (x 10) was used to examine fruits. Damage by *S. mangiferae* was based on presence of hardened, amber-coloured secretions, often sculptured with two small angled tails at one end, which remains attached to the site of oviposition (Peng and Christian 2004, 2007). Incidence was expressed as percentage of shoots containing fruits with *S. mangiferae* damage signs.

4.3.4 Assessment of mango seeds for damages

Infestation of fruits by *S. mangiferae* was determined using the procedures described by Hansen et al. (1989). Samples of between 50 and 63 young green mangoes were collected from each block on each sampling date at two weeks intervals starting eight weeks after fruit set. Only trees with a high number of fruits were selected. Fruits were incubated at the National Biological Control Unit (NBCU) laboratory at Kibaha by placing each fruit in a transparent plastic container with approximately 500 g of sterilized sand. Fruits were dissected two weeks later by using a sharp knife and inspected for the presence of larvae, pupae or adults of *S. mangiferae.* Incidence was expressed as the percentage of fruits infested by *S. mangiferae* whereas infestation rate was assessed as the number of larvae, pupae or adult *S. mangiferae* recovered per fruit.

4.3.5 Data analysis

To elucidate the overall effect which can be expected in a mango orchard, the incidences of *S. mangiferae* on developing mangoes in the field as well as the total number of incidences on incubated fruits per season were used for the calculation of the efficacy of the different treatments per season. A comparison between the numbers of recovered seed weevils per infested fruit (infestation rate) as a function of the treatments was conducted for each of the date of collection. The evaluations were done with the non-parametric multiple comparison tests (Kruskal-Wallis) followed by pairwise two-sided multiple comparison using the method of Dwass-Steel-Critchlow-Fligner (DSCF). All statistical tests were performed using SAS (version 9.3) and JMP (version 11.1.1) statistical software with P≤0.05 used as the level of significance.

4.4 Results

4.4.1 Incidence of *S. mangiferae* on developing mangoes in the field

The incidences of *S. mangiferae* in developing mangoes were significantly different between treatments during the two seasons (Table 4.1).

Table 4. 1: Pairwise statistical comparisons of treatments on the overall incidence of damage caused by *S. mangiferae* on mango fruitlets in the field and on the incubated fruits. The tests were performed using non parametric multiple comparisons (Kruskal-Wallis followed by Steel-Dwass-Chritchlow-Fligner).

Treatment comparisons	N	P *value*
Mango fruitlets		
2012/13		
O. longinoda vs Dudumida	432	0.0533^{ns}
Dudumida vs Control	432	<0.0001***
O. longinoda vs Control	432	<0.0001***
2013/14		
O. longinoda vs Dudumida	378	0.0517^{ns}
Dudumida vs Control	378	<0.0001***
O. longinoda vs Control	378	<0.0001***
Incubated fruits		
2012/13		
O. longinoda vs Dudumida	204	0.0724^{ns}
Dudumida vs Control	204	<0.0001***
O. longinoda vs Control	204	<0.0001***
2013/14		
O. longinoda vs Dudumida	252	0.0905^{ns}
Dudumida vs Control	252	<0.0001***
O. longinoda vs Control	252	<0.0001***

ns = not significant at P≤ 0.05

Incidences of *S. mangiferae* were significantly higher P<0.0001 (Kruskal-Wallis) in the unprotected plot compared to both protected plots. However, there were no significant differences between ants protected and chemically protected plots, although damage was lower in the ant treatment. Higher incidence levels were recorded in 2013/14 than in 2012/13 fruiting season. In both fruiting seasons, *S. mangiferae* oviposition sites were observed on the fruitlets only after the first four weeks of field monitoring (Figure 4.1).

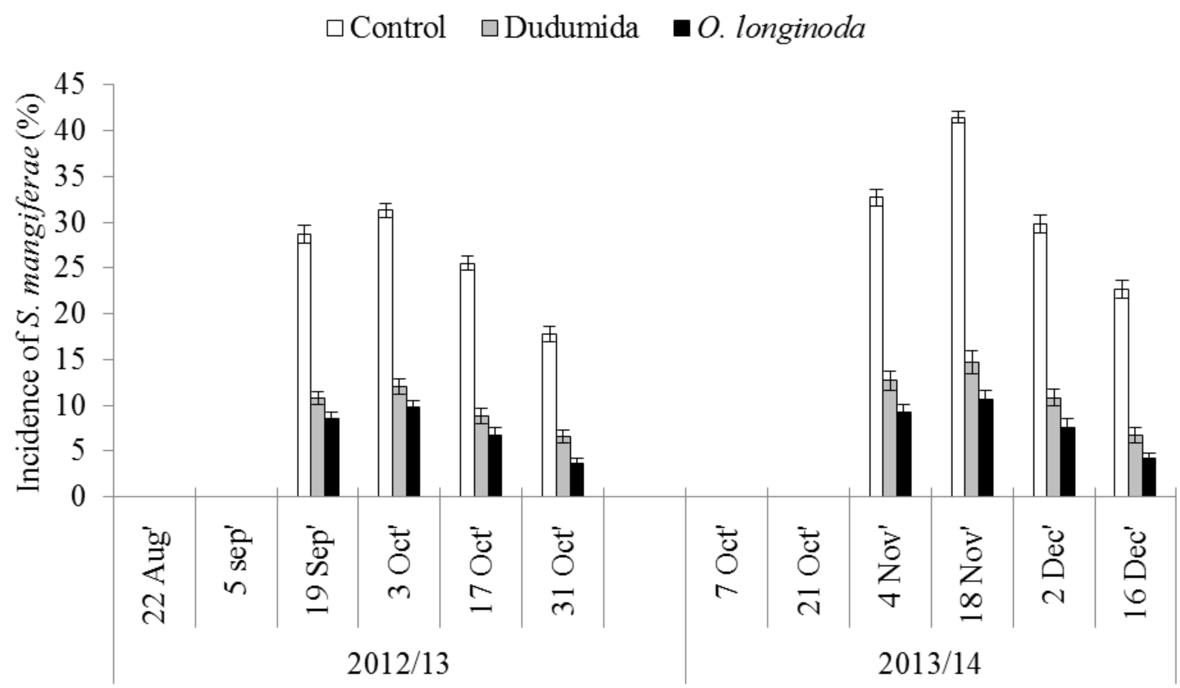

Figure 4. 1: Incidence of *S. mangiferae* on developing mango fruitlets in the field for the three treatments during 2012/13 and 2013/14 fruiting seasons at Kibaha, Tanzania. Bars show the mean (±SE) of percentage incidences.

4.4.2 Incidence of *S. mangiferae* in incubated fruits

Incidence of *S. mangiferae* infestation in incubated mangoes differed significantly among treatments whereby it was higher P<0.0001 (Kruskal-Wallis) in the unprotected plot than in the ant and insecticide protected plots. There were no significant differences (P>0.05) between the ant and the chemical treatment plots (Table 1). The incidences were generally slightly higher in 2013/14 than in the 2012/13 fruiting season (Figure 4.2).

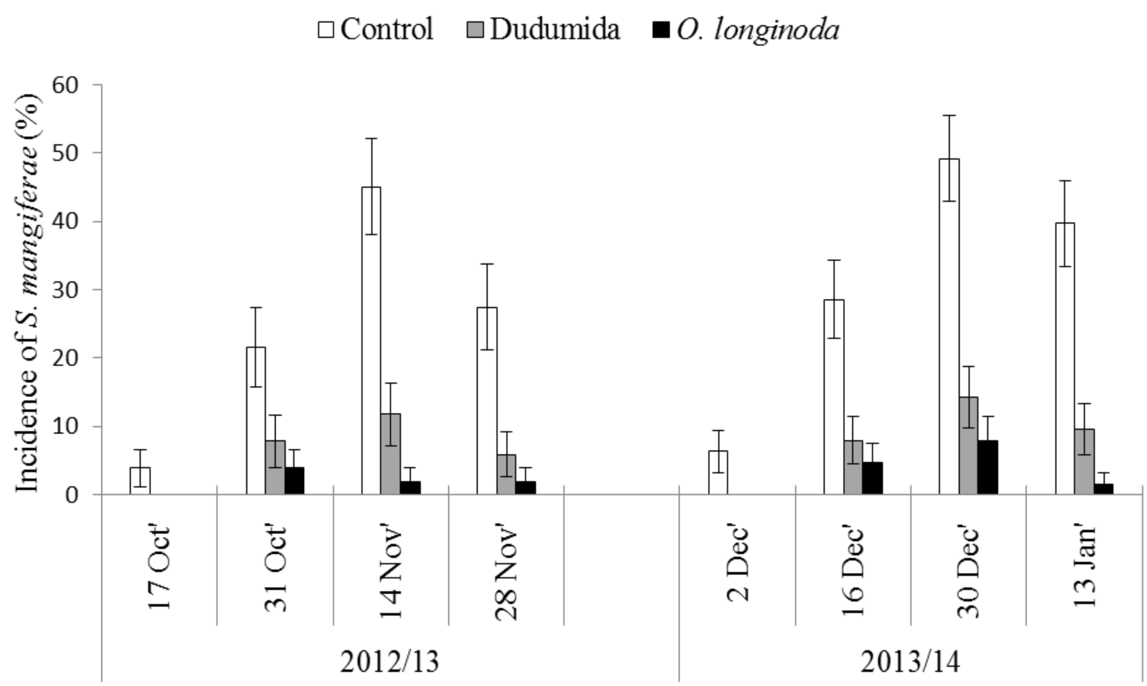

Figure 4. 2: Incidence of *S. mangiferae* on mango fruits incubated in the laboratory during 2012/13 and 2013/14 fruiting seasons at Kibaha, Tanzania. Bars show the mean (±SE) of percentage incidences.

4.4.3 Infestation rate of *S. mangiferae*

Infestation rates of *S. mangiferae* were significantly higher P<0.0001 (Kruskal-Wallis) in unprotected than in protected plots but there were no significant differences between the two protected treatments. Once again**,** higher infestation rates were recorded in 2013/14 than in the 2012/13 fruiting season (Table 4.2)**.**

Table 4. 2: **Infestation rate (number of recovered seed weevils, mean±SE) per infested fruit as a function of treatments during two fruiting seasons at Kibaha, Tanzania.**

Sampling date	**Control**	**Dudumida**	***O. longinoda***
17 Oct' 12	0.10 ± 0.07^{a}	0 ± 0.00^{a}	0 ± 0.00^{a}
31 Oct' 12	0.55 ± 0.15^{a}	0.14 ± 0.07^{ab}	$0.060.04^{c}$
14 Nov' 12	0.90 ± 0.16^{a}	0.20 ± 0.08^{b}	0.04 ± 0.04^{b}
28 Nov' 12	0.59 ± 0.15^{a}	0.12 ± 0.07^{ab}	0.04 ± 0.04^{b}
Mean 2012/13	0.53 ± 0.07^{a}	0.11 ± 0.03^{b}	0.03 ± 0.02^{b}
2 Dec’ 13	0.22 ± 10^{a}	0 ± 0.00^{a}	0 ± 0.00^{a}
16 Dec' 13	0.60 ± 0.13^{a}	0.14 ± 0.06^{b}	0.06 ± 0.04^{b}
30 Dec' 13	$1.00+0.15^{a}$	0.25 ± 0.08^{b}	0.11 ± 0.05^{b}
13 Jan' 14	0.81 ± 0.14^{a}	0.14 ± 0.06^{b}	0.02 ± 0.02^{c}
Mean 2013/14	0.66 ± 0.07^{a}	0.13 ± 0.03^{b}	0.05 ± 0.02^{b}

Different superscript letters in the same row and for the same sampling date indicate that differences are significantly different at $P \leq 0.05$ (Dwass, Steel, Critchlow-Fligner).

4.5 Discussion

The current study demonstrated that developing mangoes in the *O. longinoda* occupied trees showed significantly lower *S. mangiferae* incidence levels than in unprotected plots for the two consecutive fruiting seasons. Similar results were obtained from incubated fruits. The results were consistent for the two fruiting seasons implying that *O.*

longinoda is a robust biological control agent in the protection of mangoes from *S. mangiferae*. The mechanism behind this protection was probably partly due to the foraging behaviour of the worker ants. *Oecophylla longinoda* is predacious on a wide range of insects and other organisms that they come across during foraging on the tree canopies; flowers, developing fruits and branches. They forage on flower flushes for honeydew; and prey on adult *S. mangiferae* often before they have had a chance to oviposit successfully. Many researchers have suggested that the predatory power of *Oecophylla* is most outstanding among ants in their localities (Way and Khoo 1992; Peng et al. 2004, 2008a, b, Peng and Christian 2005, 2010; Van Mele 2008). Peng and Christian (2007) reported similar predatory behaviour by *O. smaragdina* on mango in the Northern Territory of Australia where *O. smaragdina* offered better protection than chemical insecticides against *S. mangiferae*. The current results corroborates previous results showing that weaver ants are efficient bio-control agent for a wide range of insect pests in horticultural crops (Peng et al. 2008a, b; Peng and Christian 2005; Way 1953; Vanderplank 1960; Ayenor et al. 2007; Van Mele et al. 2007; Offenberg et al. 2013).

Sternochetus mangiferae oviposition signs were first observed on mango fruitlets six weeks after fruit setting, i.e. when the fruits were still young and green as similarly observed by Shukla and Tandon (1988). Infestation increased as the season progressed and reached a peak in the middle of the season before declining towards end of the season. This was due to *S. mangiferae* females preferring laying their eggs on small to medium sized fruits (Woodruff and Fasulo 2006; Peng and Christian 2007). However, when population of *S. mangiferae* was high, even full sized fruits were accepted (Smith and Brown 2008; Hansen 1993).

Although the insecticide, Dudumida was equally effective as the *O. longinoda* in managing *S. mangiferae*, *O. longinoda* holds additional benefits as the ant has been reported to improve the fruit quality of mango and citrus (Van Mele 2008), as well as in cashewnuts (Peng et al. 2008b). The technology is also sustainable once well established; environmentally safe and compatible with organic pest management strategies (Van Mele 2008). *Oecophylla longinoda* has also been reported to improve quality and prolonged shelf life of mangoes in Benin (Sinzogan et al. 2008). *Oecophylla smaragdina* has been reported to increase net profits in citrus (Offenberg et al. 2013); mango (Peng and Christian 2005; Offenberg et al. 2013) and cashew systems in Northern Territory of Australia compared with plots protected by chemical pesticides (Peng et al. 2004). Similarly, Peng and Christian (2013) reported that weaver ant marks on fruits are positively correlated with internal fruit quality, do not induce fruit rot and can be used as an indicator of better fruit quality and safety. Insecticides on the other hand, have been reported to pose a potential risk to humans and other life forms and unwanted side effects to the environment (Igbedioh 1991). The findings in the current study agree with Peng and Christian (2007) and Materu et al. (2014) that weaver ants are either similar or better in effect than chemical insecticides in protecting mangoes from *S. mangiferae.*

4.6 Conclusion

We conclude that *O. longinoda* has the potential to serve as viable, suitable and sustainable technology in smallholder mango cropping systems. As effective biological control agents, the ants could be used either singly or as an IPM component to enhance successful suppression of *S. mangiferae* in Tanzanian mango production and facilitate access to the international export market for fresh mango fruits.

4.7 Acknowledgements

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CHAPTER FIVE

5.0 EFFICACY OF AFRICAN WEAVER ANT, *OECOPHYLLA LONGINODA* LATREILLE (HYMENOPTERA: FORMICIDAE) IN REDUCING LOSSES DUE TO FRUGIVOROUS FRUIT FLIES (DIPTERA: TEPHRITIDAE) IN SMALLHOLDER MANGO PRODUCTION SYSTEMS IN EASTERN TANZANIA

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5.1 Abstract

Fruit flies are dipteran insects that cause high losses of fruits and vegetables in the tropical and subtropical regions of the world. As quarantine pests, fruit flies affect export markets and international trade regulations. Farmers largely depend on insecticides to manage fruit flies in their mango orchards. We compared the effectiveness of *O. longinoda* with the insecticide; Imidacloprid and the untreated control against fruit flies.

Mango samples at different developmental stages were collected between September and November in (2012/13) and between November and January in (2013/14) with three-week intervals between sampling dates. Every fruit was cultured in separate individual plastic container containing approximately 500g sieved sterilized sand. Three weeks later, larvae and pupae were sieved and counted. In both years, significantly higher ($P<0.0001$) incidences and infestation rates were recorded in control plots than protected trees. Incidences and infestation rates did not differ significantly between insecticide and weaver ants protected fruits implying that *O. longinoda* is as effective as insecticides in suppressing population of fruit flies. Peak fruit fly incidences and infestation rates coincided with ripening stage of mango fruits. Our results for two consecutive years have shown that the incidences and infestation rates on mango fruits by fruit flies was lowest in the *O. longinoda* and the Imidacloprid protected trees. Thus, *O. longinoda* is an effective bio-control agent that could be exploited to serve as a vital IPM component for successful suppression of fruit flies on mango orchards.

Keywords: Bio-control, fruit flies, imidacloprid, management practices, *O. longinoda*

5.2 Introduction

Mango, *Mangifera indica* Linnaeus is one of the most important tropical fruit crops grown worldwide (Abdullahi et al. 2011; Ali et al. 2014). It is an important crop that contributes to income and livelihood of rural smallholders (Massebo and Tefera 2015). Production of mango is constrained by pests and diseases that reduce quantity and quality of produce. Fruit flies (Diptera, Tephritidae) are among the most important pests of many fruits and vegetables including mango (CABI 2004; Ekesi and Billahi 2007). Several afro tropical fruit fly species attack mango, including *Ceratitis cosyra* Walker, *C. quinaria* Bezzi, *C. fasciventris* Bezzi, *C. rosa* Karsch, *C. anonae* Graham and *C. capitata* Wiedemann. These species cause direct damages of up to 80% depending on locality, variety and season (Lux et al. 2003; Mwatawala et al. 2006; Ekesi et al. 2009). Mango damage in Africa increased since invasion by *Bactrocera dorsalis* Hendel under junior synonym of *Bactrocera invadens* Drew, Trusta and White reaching to over 80% (Ekesi et al. 2009; Ekesi et al. 2010). *Bactrocera dorsalis* is a serious quarantine pest that causes extensive economic losses to horticultural crops throughout Africa (Ekesi, 2010). Besides direct loss of produce, infestation by fruit flies cause loss of markets due to strong quarantine regulations imposed by most fruit importing countries (Massebo and Tefera 2015; Ekesi 2010; Kumar et al. 2011).

Small growers in Africa evade fruit fly infestation by early harvesting of fruits before ripening; yet, damage can still be significant (Van Mele et al. 2007). Other management options for fruit flies include spot application of baits, monitoring, mass trapping/Male Annihilation Technique (MAT), orchard sanitation, biopesticides and releases of natural enemies (Lux et al. 2003; Ekesi et al. 2010; Ouna et al. 2010; Ekesi et al. 2011; Mohamed et al. 2012; Vayssières et al. 2009). Most synthetic products used in fruit flies management are expensive and sometimes ineffective. Use of biorational methods in controlling fruit flies is highly recommended (Aluja 1996).

Studies in South East Asian countries showed that weaver ant, *Oecophylla smaragdina* Fabricius (Hymenoptera: Formicidae), was effective in controlling over 50 species of insect pests, including fruit flies (Van Mele et al. 2007). However, studies on the biological potential of an African species *O. longinoda,* in controlling fruit flies are limited to West Africa (Vayssiéres et al. 2013). Limited trials were conducted in Tanzania but results are not readily available (Z. Seguni, personal communication).

Most mangoes produced by smallholder farmers in Tanzania are destined to local markets. Thus, management practices in such production systems aim at reducing losses due to fruit flies generally, without much regard to the identity of infesting fruit fly species. This is contrary to export markets that regulated by international quarantine laws, where an exact fruit fly species found in has to be determined. Furthermore, Mwatawala et al. (2009) established *Bactrocera dorsalis* Hendel as the key frugivorous pest in low altitude warms areas of Eastern Central Tanzania. Thus any management practices targeting *B. dorsalis* will also affect minor frugivorous pests. *Oecophylla longinoda* is generalist predator previously reported to reduce infestation of mango by both *B. dorsalis* and *Ceratitis cosyra* Walker in Benin (Van Mele et al. 2007). Therefore the current study aimed at investigating the predatory ability of *O. longinoda* in reducing general losses due to fruit flies on mango.

5.3 Materials and methods

5.3.1 Description of the study site

Studies were carried out at Mlandizi, Kibaha District in the Coast region of Tanzania (S 06^{0}46'0", 038^{0}55'0"E and 73 metres above sea level) for two consecutive fruiting seasons; September to November during 2012/13 season and November 2013 to January 2014. Mango is one of the traditional fruit crops and improved varieties are grown by medium and large-scale farmers. The area is characterized by bi-modal rainfall pattern; long rainy season “Masika” extends from mid-March to mid-May and the short rainy season “Vuli” from November to early-January. Mlandizi receives mean rainfall intensity of 1023 mm per annum. The dry season, with cooler temperatures, lasts from June to October. Average annual temperatures range between 22ºC and 30ºC.

Experiments were established in a 6 year old orchard of mango variety “Apple”. Height of trees ranged between 3.5 and 4 metres, planted at a spacing of 10 by 10 metres. The experiment was laid in a plot measuring 300m x 200m, divided into (i) trees protected by *O. longinoda* (ii) trees protected by an insecticide spray, Dudumida (70WG Imidacloprid) and (iii) unprotected trees (control). Each treatment was applied to sub-plots of 51 trees in 2012/13 and 63 trees in 2013/14. Two rows of trees were left between treatments as guard rows. The experiment was replicated for two fruiting seasons, from September to November in 2012/13 and from November to January in 2013/14.

5.3.2 Suppression of competitors and introduction of weaver ant colonies in the orchard

Population of ground-nesting big-headed ant, *Pheidole megacephala* Fabricius, a strong competitor of *O. longinoda* was suppressed using GF 120 (0.02% Spinosad®) mixed at a ratio of 90 ml finely ground fish meat: 20ml GF 120: 40 ml water. We then introduced 16 colonies of *O. longinoda* into the experimental orchard six months before start of mango fruiting season, following procedures by Peng and Christian (2005). Each transplanted weaver ant colony was given access to a range of four to six trees and about 6 – 12 nests were introduced on each mango tree depending on canopy size. A ring of sticky barrier was established near the base of the trunks to prevent colonization of treesby ground nesting competitors (Offenberg and Wiwaitwitaya 2010). Trees colonized by *O. longinoda* were monitored once every month, regularly suppressing weaver ants competitors (whenever found), replacing weak colonies, feeding the ants with sugar, water and protein during food scarcity periods. Trees colonized by same colonies were connected by nylon ropes (> 3mm in diametre) to facilitate easy communication within the colony.

5.3.3 Fungicide sprays

In the insecticide treatment, a systemic broad spectrum fungicide, Megasin – M 70% WP (70% Thiophanate methyl) was applied at the rate of 100g/tree three times in a season, to control powdery mildew disease, *Oidium mangiferae* Berthet as per manufacturer's recommendations. Additionally, in the entire experiment potassium nitrate was applied at the rate of 10g/tree three times each season to induce uniform flowering of mango trees.

5.3.4 Insecticide sprays

The insecticide, Dudumida (70WG Imidacloprid, Mega Generics Limited, Tanzania) was applied at the rate of 10 ml/tree to control chewing and sucking insect pests. Spraying was done early in the morning (06:00-07:00 hours) to avoid spray drift. The first spray was done at the onset of flowering, repeated at three-week intervals (as per manufacturer's recommendations). The insecticide was sprayed four times each season.

5.3.5 Effects of management practices on incidence and infestation rates of fruit flies

A repeated measures design was used to determine incidence and infestation rates of fruit flies over time, with mango trees as within treatment subjects. Fruits were collected at three-week intervals for the two fruiting seasons, starting fourth week of September to the fourth week of November in 2012/13 and from second week of November 2013 to second week of January 2014 in 2013/14. The fruit samples were collected following procedures by Walker et al. (1997) and brought to the laboratory at Kibaha Biological Control Unit for culturing. We harvested from each plot 51 fruits in 2012/13 and 63 fruits in 2013/14 on every sampling date.

Each fruit was cultured in a clear plastic container containing approximately 500g of sieved, sterilized fine sand at the base and a lid with fine gauze for ventilation. Containers with the fruits were monitored everyday. Sand was changed whenever necessary to prevent emerging larvae from dying. Plastic containers with the fruits were stored in large wooden rearing cages (1m x 1m x 1m) with a fine gauze fabric for ventilation on the sides and a wooden base. Base of large wooden rearing cages were smeared with petroleum jelly to prevent the cultured samples from *Pheidole megacephala* ant attack. Fruits were left in the laboratory for three weeks at ordinary room temperatures (28 – 30^0C) before discarding.

Emerged larvae and pupae from the fruits were then sieved from sand and placed into individual petri dishes and counted using procedures described by Ekesi and Billah (2007). Incidence was recorded as percentage of infested fruits per sub-plot. Infestation rate was expressed as the number of recovered puparia per infested fruit. Thus the recorded data for the three compared treatments were the incidence and the fruit fly infestation rate.

5.3.6 Effects of management practices on fruits yield

A nested design was used to determine effects of treatments (groups) on mango yield of individual mango trees (subgroups). At harvesting, fruits from each tree in a treatment were counted and recorded. Thus, yields were expressed as the number of healthy fruits per tree.

5.3.7 Data analysis

The collected data for both incidences and infestation rate by fruit flies was Arcsine transformed before analysis. The equality of means on the effect of treatments on infestation rates by FF was tested by using two way repeated measures ANOVA which was done independently for each season. Bonferroni multiple comparison tests was used to evaluate the treatments in terms of incidences and infestation rates. The association between treatment and sampling time on incidence was tested using Chi-square. To determine whether mango yield differ among treatments, nested ANOVA was used for comparison. For each season, yield was tested separately. The JMP (version 11.1.1) statistical discovery (SAS Institute Inc., Cary, North Carolina) was used for all analyses. All statistical tests for significance were performed at $P \leq 0.05$.

5.4 Results

5.4.1 Number of cultured fruits

In total, 1368 mango samples were cultured during the two fruiting seasons. Number of sampled fruits is summarized in Table 5.1.

Table 5. 1: Number of sampled mango fruits for the two fruiting seasons at Kibaha, Coast region, Tanzania

Fruiting seasons	**2012/13**	**2013/14**
Total Number of fruits sampled	612	756
Minimum number of pupae/fruits	4	4
Maximum number of pupae/fruit	26	29
Total number of recovered pupae	667	1049
Average number of pupae per fruit	1.09	1.39

5.4.2 Effects of management practices on incidence of fruit flies

Fruit flies incidences were lowest in fruits protected by *O. longinoda* and the insecticide treatments. Unprotected fruits had highest incidences of fruit flies. During early stages of fruit development, i.e. on immature fruits no fruit fly incidences were recorded. However, incidences by fruit flies were recorded on mature green fruits and reached the peak during full ripening stage. A decline in incidence by fruit flies was noted towards end of the season (Figure 5.1).

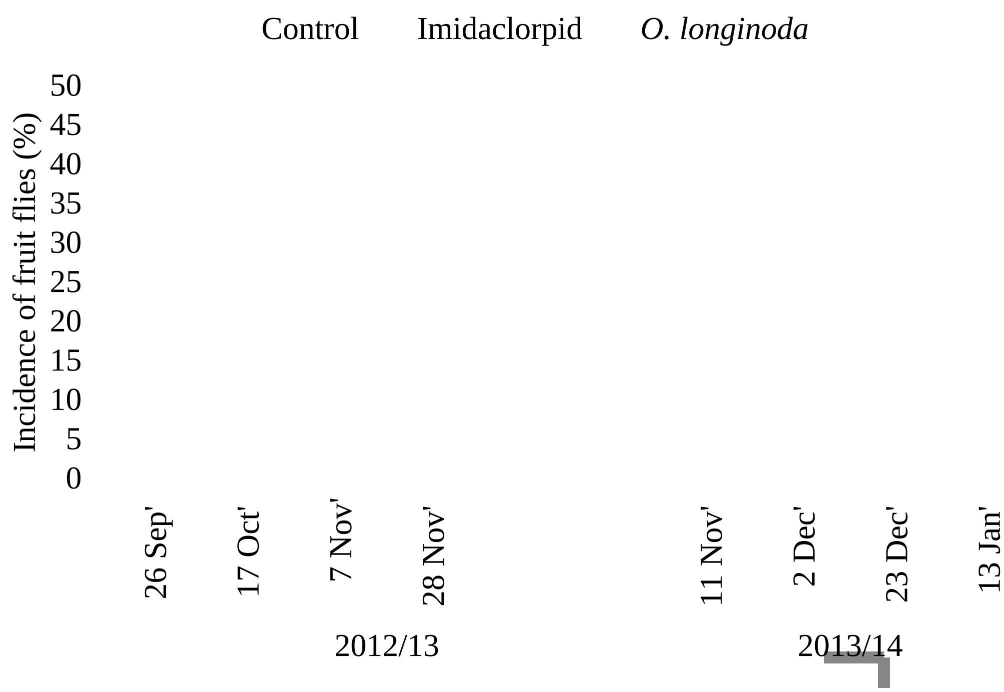

Figure 5. 1: Incidence of fruit flies (mean±SE) on cultured mangoes for the three compared treatments during 2012/13 and 2013/14 fruiting seasons at Mlandizi in Kibaha,

We observed significant association between incidence and management practices (Table 5.2). High incidences in the control did not occur by chance.

Table 5. 2: Association between fruit fly incidence and control measures (Kruskal Wallis)

Weeks after first spray of an insecticide	**Df**	χ^2	***P value***
2012/13			
Three	2	10.124	0.0063
Six	2	22.740	<0.0001
Nine	2	10.467	0.0053
2013/14			
Three	2	10.048	0.0066
Six	2	25.645	<0.0001
Nine	2	21.648	<0.0001

5.4.3 Effects of management practices on infestation rate by fruit flies

The infestation rate followed a similar trend to that of fruit flies incidences. The lowest infestation rate was recorded in fruits protected by *O. longinoda* and the Imidaclorpid protected trees. Infestation rates was recorded when the fruits were mature but still green and increased as the season progressed, also reaching a peak when fruits were ripe (Figure 5.2).

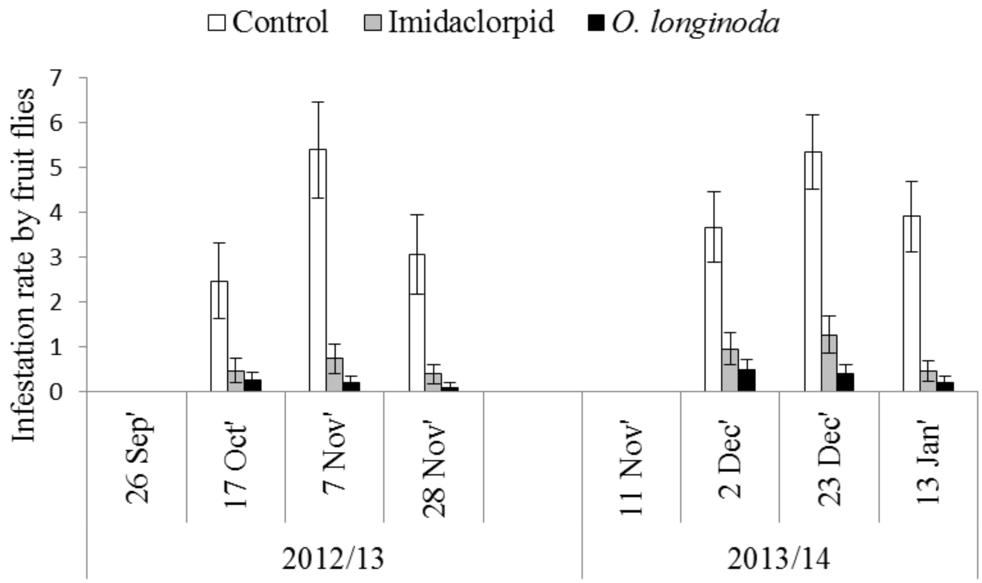

Figure 5. 2: Comparison on the effect of different treatments on the infestation rate by fruit flies recorded from cultured mango fruits during 2012/13 and 2013/14 fruiting seasons at Mlandizi in Kibaha district.

Fruit fly infestation rate varied significantly among treatments in 2012/13 ($F_{(2,\ 199)}$ = 21.246, *P<0.0001*), time ($F_{(3,\ 200)}$ = 9.52, *P<0.0001*) and treatment x time (Wilk's lambda test $F_{(6,\ 398)}$ = 3.553, *P = 0.0019*). Similarly, in 2013/14 infestation rate varied significantly among treatments ($F_{(2,\ 247)}$ = 36.286, *P<0.0001*), time ($F_{(3,\ 248)}$ = 14.085, *P<0.0001*) and treatment x time (Wilk's lambda test $F_{(6,\ 494)}$ = 4.714, *P = 0.0001*) (Table 3). Infestation rates were significantly higher in the control than in protected trees, excepted during the first three weeks of sampling (Table 5.3). However the infestation rates of fruit flies in mango were not significantly different between insecticide and weaver ant's treatments.

Table 5. 3: Bonferroni multiple comparison tests of FF infestation rate on different treatments for the two cropping seasons at Mlandizi in Kibaha district.

	P values			
Paired treatments	**Interval (weeks)**			
2012/13	3	6	9	12
Weaver ants vs Imidaclorpid	ns	ns	ns	ns
Weaver ants vs Control	ns	*	***	***
Imidacloprid vs Control	ns	*	***	**
2013/14				
Weaver ants vs Imidaclorpid	ns	ns	ns	ns
Weaver ants vs Control	ns	**	***	***
Imidacloprid vs Control	ns	***	***	***

ns = not significant at $p < 0.05$; *** $P<0.001$; **: $p<0.01$; *:$p<0.05$

5.4.4 Effects of management practices on fruits yield

The results on yields have shown significant differences ($P<0.0001$) between the control and the protected fruits for both seasons. Similarly, no significant differences in yields ($P>0.05$) were found between the *O. longinoda* and Imidacloprid protected trees. A similar trend was observed in both fruiting seasons. Imidacloprid treatment recorded highest number of fruits per tree, followed by the *O. longinoda* and the lowest yield recorded in the control treatment (Figure 5.3).

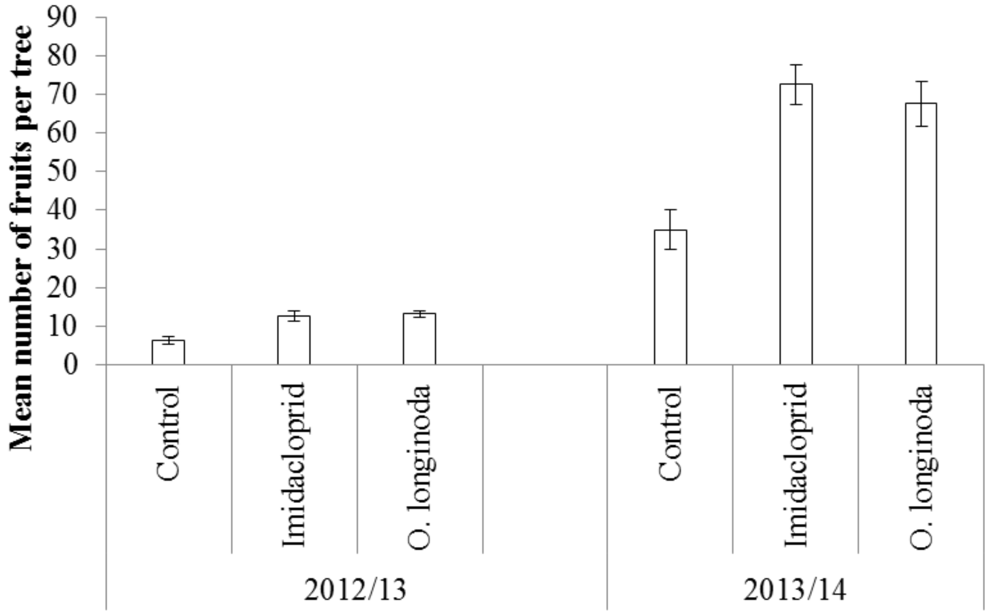

Figure 5. 3: Comparison of number of harvested fruits per tree on the effect of different treatments during 2012/13 and 2013/14 fruiting seasons at Mlandizi in Kibaha district.

Trees protected by *O. longinoda* and Imidacloprid produced significantly higher fruit yield than unprotected trees ($F_{(2, 48)}$ = 6.867; *P = 0.0024* in 2012/13 and $F_{(2,, 60)}$ = 5.754; *P = 0.0052* in 2013/14). Conversely there were no significant differences between the former two treatments (P>0.05).

5.5 Discussion

We assessed in the present study, the incidence and infestation rates of tephritids in mango fruits generally. We did not determine the number and species of emerged adult flies, given the fact that the main interest was losses incurred by smallholder farmers targeting local markets. However, previous studies indicated that *B. dorsalis* is the dominant fruit fly species attacking mango (Mwatawala et al. 2004) that has competitively displaced the native *C. cosyra* (Ekesi et al. 2009). Incidence of *B. dorsalis* in mango can be as high as 59.7% (Mwatawala et al. 2009). Our results for the two consecutive years showed lowest incidences of fruit flies in the *O. longinoda* and the Imidacloprid protected trees. Furthermore, incidence of fruit fly was lower when the fruits were harvested before ripening, suggesting that colour, smell and other characteristics associated with fruit ripening played an important role in attracting fruit fly for oviposition. This is because during ripening, fruits change in attributes such as colour, tissue firmness, volatile aroma production, starch accumulation and quantities of other organic compounds (Kumar et al. 2011). Peak fruit fly incidences were recorded in November in 2012/13 and December in 2013/14, coinciding with peak ripening stage of mango fruits. Faiza et al. (2012) reported similar observations on guava in Sudan. The *Apple* variety used in this study has a smooth skin, shiny yellow/orange colour and strong aroma when ripe, high juice content and excellent flavour which attracted the fruit flies for oviposition (Kumar et al. 2011).

Weaver ants are generalist predators and fearless foragers, tirelessly scouting trees in search of palatable pests, including fruit flies. They either deter adults from ovipositing or feeding on fruits. Presence of *O. longinoda* in mango orchards has been reported to deter adult female fruit flies from ovipositing (Van Mele et al. 2007; Peng and Christian 2006). Similarly, Van Mele et al. (2007) as well as Offenberg and Wiwatwitaya (2010) reported that weaver ants control a wide range of pests through direct predation and foraging. Indirect control through deterrence and disturbance of fruit flies during oviposition was probably the most important causes of reducing fruit fly damage but had not been proven. Although the presence of *O. longinoda* hinders fruit fly from depositing their eggs, other olfactory or visual factors equally played an important role in deterring the pests (Van Mele et al. 2009; Adandonon et al. 2009). The findings from the present study corroborate to the findings by Vayssiéres et al. (2013) who reported that weaver ants leave their ant cues while patrolling on fruits that could deter any fruit fly species and many other insect species seeking an oviposition or feeding site.

The lower number of fruit fly puparia recorded on the trees protected by *O. longinoda* in both years was attributed to the physical deterrence behaviour exhibited by *O. longinoda* in driving away fruit flies. Ativor et al. (2012) reported similar deterrence effect of *O. longinoda* on citrus orchards in Ghana. Our findings suggest that after *O. longinoda* have landed on mangoes, fruit flies turn away completely or may lay much fewer eggs. Van Mele et al. (2009) found that adults of fruit flies are more affected through repellence by ant cues than by direct predation. A study under green house conditions in Benin revealed that the density of ant pheromone, significantly affected the oviposition time and the number of fruit fly pupae collected per kilogramme of fruit (Adandonon et al. 2009). Fewer number of puparia recoveries could also be explained by the oviposition behaviour of fruit fly and foraging aggressiveness of *O. longinoda*. The adult fruit fly need to spend a considerable time during their search in locating a suitable oviposition site on the fruit, drilling a hole, laying eggs, and then leaving. Due to aggressive behaviour of *O. longinoda*, there was a reduction in the duration of stay of fruit fly adults on mango fruits in the presence of abundant *O. longinoda*. This is because the fruits were frequently patrolled and the adults of fruit flies were chased away often before ovipositing successfully on a fruit as it was also observed by Ativor et al. (2012). In field observations, Peng and Christian (2006) demonstrated that 11 minutes were required for a fruit fly to successfully oviposi, suggesting that the oviposition activity of fruit fly was greatly affected by the abundance of *O. longinoda*. The success of *O. longinoda* as effective biocontrol agents is attributed to their pronounced territoriality, permanent surveillance (all year round, day and night), and very efficient recruitment strategy as well as quick response to increase in prey numbers (Offenberg and Wiwatwitaya 2010).

The lower yields recorded in 2012/13 compared to that of 2013/14 was probably due to the environmental conditions that resulted into reduced flowering and subsequently impaired fruit set. Griesbach (2003) working on mango reported some cultivars like *Apple* have tendency of alternating the bearing, i.e. a heavy bearing season followed by a poor season. As such, the observed scenario was not peculiar. Despite the variation in fruit bearing higher yields were recorded in the weaver ants and Imidacloprid protected trees compared to unprotected control in both fruiting seasons suggesting that much yields was lost due to pests. High fruit fly infestation is believed to have caused early fruit drop which led to lower yields. The extensive level of observed fruit drop particularly in the 2013/14 season suggest that not only fruit fly piercing of the fruits for egg laying caused the loss but also other factors associated with the infestation process. Kumar et al. (2011) and Vayssières et al. (2009) showed that some females'of fruit fly species carry bacteria that they injected into the fruit during oviposition. Consequently, the fruit tissues surrounding the eggs decay faster to ease release of fruit juices and to allow suitable environment for newly hatched larvae. Larvae that hatch from the eggs feed on the decaying fruit tissue, and on the yeasts and bacteria that multiply in it, thus making it more nutritious for the larvae (Sarwar, 2015). From a quantitative point of view, the damage is caused by larvae at the second and especially third instar stages, by the removal of significant proportion of the pulp which results in reduction in the yield and quality of the harvestable fruits (Badii et al. 2015). The larval feeding results in some cases fruit drop to the ground as, or just before the maggots pupate and emerge as adult to continue the cycle (Ekesi and Billah 2007).

5.6 Conclusion

Incidences and infestation rates of *B. dorsalis* were similar in *O. longinoda* and insecticide-protected fruits suggesting that, *O. longinoda* is as effective as insecticides in suppressing population of fruit flies.Despite the similarity in effectiveness, the application of broad-spectrum synthetic pesticides is discouraged because of health, environment, socio-economic problems as well as insect resistance and resurgence Thus, *O. longinoda* can serve as a vital IPM component and an alternative to insecticides for successful suppression of the fruit flies to lower population levels.

5.7 Competing Interest

The authors declare that they have no competing interests.

5.8 Authors' Contributions

Nassor R. Abdulla (NRA), Gration M. Rwegasira (GMR) and Maulid W. Mwatawala (MWM) built the concept and designed the study, NRA, GMR and MWM laid, conducted the experiment and collected the relevant data, NRA, GMR and MWM analyzed data and interpreted the results. NRA drafted the manuscript, GMR and MWM revised the manuscript. All authors read and approved the manuscript before submission.

5.9 Acknowledgements

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CHAPTER SIX

6.0 GENERAL CONCLUSIONS AND RECOMMENDATIONS

6.1 General Conclusions

The two year studies have demonstrated the African weaver ants (*Oecophylla longinoda*) to be very effective bio-control agents comparable to the currently recommended insecticides against major cashew and mango insect pests. As the use of weaver ants is sustainable, this technology' provides a rare example of sustainable pest management technique that matches conventional yields with the bonus of being more cost-effective and generally safer because certified organic produce can fetch higher prices. Therefore, *O. longinoda* can serve as a reliable alternative to insecticides in protecting cashew and mango against insect pests in Tanzania. However, the potential for *O. longinoda* technology is high not only in cashew and mango but also in other tropical tree crops especially considering a worldwide increase in demand for organic products and sustainable pest management strategies. Furthermore, the studies have shown that artificial feeding of ants lead to higher ant abundance compared to conditions where ants had access only to naturally occurring food. As high weaver ant densities are linked to maximum and consistent protection of tree crops, supplementary feeding could play an important role in promoting their biological control activities. Nevertheless, in the present study, the increase in ant abundance due to feeding did not translate into significantly reduced levels of pest damage and increased yields because the abundance of ants was maintained at high densities in both ant treatments. However, ants feeding benefit farmers in long term scenarios since feeding leads to more stable and persistent *O. longinoda* populations. Feeding of *O. longinoda* may improve its ability to resist competition and in this way afford better pest control. Thus, the fed *O. longinoda* colonies may have been better at withstanding the attacks and competition from other ant species like *Pheidole*, compared to the non-fed colonies. It is evident that a strong colony defends its territory unlike the weak, non fed colonies.

6.2 Recommendations

Based on the findings in the present study, the following recommendations are made: -

(i) The use of *Oecophylla longinoda* has to be encouraged in controlling cashew and mango pests particularly when organic farming is a priority.

(ii) More advanced research should focus on understanding and managing *O. longinoda* enemies, i.e. *Pheidole megacephala* and crazy ants. Also, broad spectrum insecticides should be avoided in the orchards to ensure effective use of *O. longinoda* technology.

(iii) Further research be conducted on the potential use of *O. longinoda* in areas where the predator does not naturally exist to allow further promotion and expand the avenues for the technology.

LIST OF PUBLICATIONS (PEER REVIEWED JOURNAL PAPERS) (ABSTRACTS)

Paper 1: Effectiveness of *Oecophylla longinoda* Latreille (Hymenoptera: Formicidae) in Managing Major Insect Pests in Organic Cashew Production Systems

Manuscript submitted to the '*Journal of Organic Agriculture'* (Under Review)

By

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Abstract

Cashew production in Tanzania is severely constrained by sucking insect pests such as the coreid coconut bugs (*Pseudotheraptus wayi* Brown), the mirid bugs, *Helopeltis* spp and Thrips spp. These pests damage flushing foliar and floral shoots as well as young cashew fruits and nuts. Farmers rely heavily on insecticides to control these pests and there are no suitable alternative control methods compatible with organic cashew production. Weaver ants, *Oecophylla longinoda* Latreille have for long been considered as effective biological control agents against sap-sucking pests of cashew but studies on their effectiveness as compared to conventional insecticides had never been conducted. The current study evaluated the efficiency of *O. longinoda* as compared to the recommended conventional insecticide, lambda cyhalothrin (Karate®) in controlling major cashew insect pests and compared the resulting cashew yield. The damage caused by each pest was significantly lower (P<0.0001) on trees with weaver ants and in the plots treated with Karate® than was the case on the control trees. There were no significant differences (P>0.05) in the damage between *O. longinoda* and Karate® treated trees suggesting that the two treatments are equally effective. Yield increases of 58.2% and 60.7% in the insecticide treated trees and in the *O. longinoda* protected trees, respectively were obtained, in relation to untreated control plots during the two seasons. Thus, *O. longinoda* can serve as an alternative to chemical insecticides for protection of cashew in Tanzania.

Keywords

Cashew, lambda-cyhalothrin, Naliendele, *Oecophylla longinoda*, organic production, sucking insect pests

Paper 2: Effect of Supplementary Feeding of *Oecophylla longinoda* on Their Abundance and Predatory Activities Against Cashew Insect Pests

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By

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Abstract

Many studies have shown the efficiency of using weaver ants (*Oecophylla* species) as natural bio-control agents against agricultural pests. Supplementary feeding could promote fast growth of this ant's population and discourage them from moving away. However, such artificial feeding might slow down ant´s search rates and in this way make them less efficient bio-agents. The experiments were conducted for two consecutive seasons at Naliendele Reseach Station. Cashew trees planted at a spacing of 12 m x 12 m in 2002 were used to investigate whether supplementary feeding could enhance foraging behaviour of *O. longinoda*. Fed *O. longinoda* colonies (FWA) were supplemented with a 30% sugar solution and approximately 22 g of finely ground fish meat at two-week intervals while the un-fed colonies (UWA) had access to only naturally occurring food sources. Weaver ant densities and pest damage was monitored fortnightly on newly damaged shoots, panicles and fruits and nut yields assessed after each harvest season. The results revealed that there was a significant difference ($P<0.05$) with higher weaver ant densities in the FWA compared to UWA colonies and significantly lower ($P<0.05$) pest damage levels were recorded on weaver ant treatments compared to plots without weaver ants. No significant differences ($P>0.05$) in yields and mean damage levels were recorded between the two weaver ant treatments. Highest nut yields (4.22±0.30kg/tree and 5.37±0.27kg/tree) were recorded in the fed colonies, followed by non-fed colonies (4.20±0.30kg/tree and 4.88±0.24kg/tree) and the least (2.66±0.19kg/tree and 2.99±0.19kg/tree) was recorded from the untreated controls in 2012/13 and 2013/14, respectively. The studies indicated that supplementary feeding could boost weaver ants to higher population levels without reducing their effectiveness as biocontrol agents.

Keywords: Ant feeding, biocontrol agents, *O. longinoda*, predatory activities, supplementary feeding.

Paper 3: Mango Seed Weevil, *Sternochetus mangiferae* (Curculionidae: Coleoptera) Could be Effectively Controlled by the African Weaver Ant, *Oecophylla longinoda* Latreille

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By

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Abstract

The mango seed weevil, *Sternochetus mangiferae* (Fabricius), is among the major threats to mango production in Tanzania. *Sternochetus mangiferae* is primarily a quarantine pest whose presence inside the fruits restricts access to new foreign markets and leads to rejections of fruits destined for export. Management options for the pest have largely been dependent on field sanitation and application of synthetic insecticides with some success. Thus, more sustainable methods are needed to substitute insecticides, as this may also open up opportunities for organic markets. We conducted field experiments for two fruiting seasons in a mango plantation at Mlandizi, Kibaha district along the coastal belt of Tanzania to evaluate and compare the effectiveness of the predaceous ant *Oecophylla longinoda* Latreille with foliar insecticidal sprays of Dudumida (70 WDG Imidacloprid) in controlling *S. mangiferae*. Mango seed weevil infestation was assessed fortnightly based on infestation marks on developing fruits starting eight weeks after fruit set to early ripening phase. Between 50 and 64 fruits were sampled, well labelled in jute bags, secured and transported to the laboratory at Kibaha Biological Control Unit (KBCU) for incubation at room temperature using rearing transparent containers. Two weeks later, the fruits were dissected and inspected for presence of *S. mangiferae* developmental stages. Field and laboratory results indicated that fruits from trees that were occupied by *O. longinoda* and from those treated with insecticide showed significantly ($P<0.0001$) lower incidences and infestation rates by *S. mangiferae* than untreated trees. Furthermore, there were no significant differences between the insecticide and the weaver ant treatments. We conclude that in our experiments *O. longinoda* is an efficient biological control agent for a long term control programme and comparable to insecticide (Dudumida) in suppressing *S. mangiferae* and may be used in Tanzanian mango plantations.

Keywords Dudumida, insecticides, *Sternochetus mangiferae,* quarantine regulations, weaver ant.

Paper 4: Efficacy of African Weaver Ant, *Oecophylla longinoda* Latreille (Hymenoptera: Formicidae) in Reducing Losses due to Frugivorous Fruit Flies (Diptera: Tephritidae) in Smallholder Mango Production Systems in Eastern Tanzania

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Abstract

Fruit flies are dipteran insects known to cause devastating losses of fruits and vegetables in the tropical and subtropical regions of the world. As quarantine pests, fruit flies have detrimental effects on the export market due to international trade regulations. Farmers are largely dependent on using insecticides to manage fruit flies in their mango orchards. We compared the effectiveness of *O. longinoda* with the insecticide; Imidacloprid and the untreated control against fruit flies. Mango samples at different developmental stages were collected between September and November in (2012/13) and between November and January in (2013/14) with three-week intervals between sampling dates. Every fruit was cultured into separate individual plastic container containing approximately 500g sieved sterilized sand. Three weeks later, larvae and pupae were sieved and counted. For both years, significantly higher ($P<0.0001$) incidences and infestation rates were recorded in control plots than protected trees. Incidences and infestation rates did not differ significantly between insecticide and weaver ants protected fruits implying that *O. longinoda* is as effective as insecticides in suppressing population of fruit flies. Peak fruit fly incidences and infestation rates coincided with ripening stage of mango fruits. Our results for two consecutive years have shown that the incidences and infestation rates on mango fruits by fruit flies was lowest in the *O. longinoda* and the Imidacloprid protected trees. Thus, *O. longinoda* is an effective bio-control agent that could be exploited to serve as a vital IPM component for successful suppression of fruit flies on mango orchards.

Keywords: Bio-control, fruit flies, imidacloprid, management practices, *O. longinoda*