SOKOINE UNIVERSITY OF AGRICULTURE

FACILITATING INTERNATIONAL AGRICULTURAL TRADE THROUGH SCIENCE: THE CASE OF TEPHRITID FLIES

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By

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Professorial Inaugural Lecture

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About the Author

Prof. Maulid Walad Mwatawala was born on 1st November 1970, in Mbeya Municipality. He received secondary education from Sangu and Mazengo Secondary schools of Mbeya and Dodoma regions respectively.

He later obtained Bachelor of Science (1995), Master of Science in Agriculture (1998) and PhD (2008) all from Sokoine University of Agriculture (SUA).

He also graduated in Bachelor of Laws (LLB, Hons.) from Open University of Tanzania (OUT) in 2013 and Master of Law in Information Technology and Telecommunication (LLM IT&T) which is jointly offered by OUT and the United Kingdom Telecommunications Academy (UKTA) in 2015.

He started his professional career at SUA in December 2000 as an Assistant Lecturer in the Department of Crop Science and Horticulture (DCSH). He then rose to the ranks of Lecturer (2005), Senior lecturer (2008), Associate Professor (2011) and finally Professor (2017). He teaches courses in Applied Entomology, Organic Farming and (Agricultural) Legislations, Reduction of Post-Harvest Losses and Wastages through Good Agricultural Practices (GAPs).

Prof. Mwatawala is a member of the Governing Council of the Tropical Pesticides Research Institute (TPRI); a member of Ministerial Advisory Board (MAB) of the Tanzania Food and Drugs Agency (TFDA); Chairman of the Plant Quarantine and Phytosanitary Sub - committee (PQPS) of the Ministry of Agriculture, Livestock and Fisheries. He is also a Vice Chairman of the Tanzania Entomological Association (TEA).

Prof. Mwatawala served as Editor in Chief of Tanzania Journal of Agricultural Sciences (TAJAS), between 2012 and 2016. His current research focuses on ecology and management of fruit flies. He is currently the Head of the Department of Crop Science and Horticulture DCSH, a position he has held since August 2017.

He was involved in projects on Integrated Pest Management (IPM) for fruit flies in Tanzania; Increasing value of African mango and cashew (funded by DANIDA, Resolution of cryptic species complexes of tephritid pests to overcome constraints to SIT application; enhanced fruits preservation using nano technology.

Prof Mwatawala has published 64 articles in peer reviewed journals, one book chapter and numerous conference papers and extension materials. He received a number of awards including the Best Student Award by the Ecological Society for East Africa (ESEA) in 2008.

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I would like to thank all the Donors who supported my research work; The Belgian Development Cooperation (DGOS), The International Atomic Energy Agency (IAEA), International Foundation for Science (IFS) and Danish International Development Agency (DANIDA). The works I did would never have been possible without their financial and material support.

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I would like to acknowledge the support from my family, my wife Natasha, and my children Shaquille, Haaris and Faaris and my niece Mulhat. Last but not least, I would like to thank everyone who has helped me in one way or another during my tenure as a student at SUA, in my academic career as a researcher and a professor.

Foreword

Mr. Chairman
Vice Chancellor
Deputy Vice Chancellors
Principals, Dean, and Directors
Colleague Professors
Member of Academic Staff
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Distinguished Invited Guests
Ladies and Gentlemen

I am greatly honoured to stand before you to deliver this lecture on the role of science in facilitating international agricultural trade. My talk focuses on fruits trade as affected by a group of insects collectively known as fruit flies or Teprhritids. Most of us have heard about fruit flies because of the contribution of Drosophildae in genetics studies. However, the group I am referring to in this lecture is the "true fruit flies", which is different from Drosophilidae "the fruit flies of genetics lab". The behaviour of the two groups is different. Drosophila feed on dead decomposing matter, while Tephritids attack healthy fruits. My inspiration on fruit flies came from by the then Director of SUA Pest Management Centre (SPMC) Prof. Robert Machang'u through the then Head of Department of Crop Science and Production Prof. Amon Maerere. How it started was that Prof Machang'u liked his guava fruit, but was always annoyed by maggots crawling inside his beloved fruits. He shared his distaste to a Belgian colleague who told him about fruit flies research at the Royal Museum for Central Africa (RMCA) of Tervuren, Belgium under Dr Marc De Meyer. The link with RMCA was established and a proposal was developed for a research project which was funded by the Belgian Development Cooperation Agency (DGOS). I became a PhD student under the project; and that was the start of my journey in the fruit flies research. Over the years, from 2004 we have been researching on fruit flies and have contributed substantially to the literature on ecology, biology and management of this group of pests. Today SUA is regarded as a Centre of expertise on this group of flies and the University is now a champion of an international course on fruit fly systematics and ecology. I feel humbled because, sincerely speaking, I never dreamt of becoming an academic, let alone being an applied entomologist. When I graduated with Master;s degree from SUA in 1998 ago I joined my friends and we formed a company called Fortune Media and registered an entertainment magazine called Rockers. However my fate, it seems, was to become what I am today. So today, I am going to share with you our research findings we have gathered over the years and how information we generated has contributed to international fruits trade. Throughout my talk, I will be highlighting specific roles played by SUA.

Abstract

International agricultural trade is important in addressing spatial and temporal food shortages across the globe. Agricultural trade generates income and contributes to economies of many countries. Unfortunately, there are various risks associated with the movement of agricultural commodities across borders. The spread of pests across countries is one of the great risks. The International Plant Protection Convention (IPPC), which is an agreement between nations, aims at preventing and controlling the introduction and spread of pests of plants and plant products across national boundaries. IPPC formulates various standards and guidelines that can be adopted by member states to formulate municipal phytosanitary laws against the introduction of pests. Countries normally conduct Pest Risk Analysis (PRA) in order to facilitate agricultural trade. This process requires scientific evidence on the identity and occurrences of pests in an area and a possible entry and the establishment and the spread of those pests into exotic places. Fruits and vegetable trade is important for food and security among the global population. However, fruit trade introduces the risk of the spread of pests, including fruit flies. Most fruit flies cause heavy losses to the fruit industry and these are therefore of quarantine importance. Research which has been conducted across the globe provided scientific evidence on the possible spread of fruit flies in order to facilitate trade. The Sokoine University of Agriculture (SUA) collaborated with various partners in the world to generate important information that is a prerequisite for conducting PRA. This inaugural lecture highlights key findings that include identification of new species, resolution of cryptic species, host range and preference, spatial and temporal distribution, and mitigation options against the selected economically important fruit flies.

Key words: International trade, fruits, fruit flies, quarantine

Contents

1.0 International agricultural trade

1.1 Importance of international agricultural trade

Food production is not uniform across regions of the world because of inherent climatic variations and other reasons. Spatial and temporal variation in food shortages is therefore a common phenomenon. There is no country in the world that is permanently food sufficient. There are people who are malnourished or undernourished even in countries with agricultural surpluses. There are over 800 million people in many countries – particularly in Africa and Asia – who are still suffering from hunger (WHO). Agricultural trade therefore helps to address food production shortages and contributes to farmers' income and economic growth of these countries. The expansion of agricultural trade has helped provide greater quantities, wider variety and better quality food to increased numbers of people and at lower prices. Agricultural trade also generates income and gives a sense of wellbeing to the millions of people who are directly or indirectly involved in it. At the national level, in many countries agricultural trade is a major source of foreign exchange which is necessary to finance imports and development programmes.

1.2 Risks associated with international agricultural trade

International agricultural trade involves movements of bulk quantities of food across borders. Such a trend poses a great risk of introducing pests associated with such cross border commodities to exotic areas. Such risks have to be contained in order to facilitate international movement of agricultural products. The International Plant Protection Convention (IPPC) is a 1951 multilateral treaty instituted by the United Nations Food and Agriculture Organisation (UN FAO). The treaty aims at securing coordinated, effective action of preventing and controlling the introduction and spread of pests of plants and plant products. Thus, the Convention extends beyond the protection of cultivated plants to the protection of natural flora and plant products. The Convention is recognized by the World Trade Organisation's (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) as the only international standard setting body for plant health. For example, the International Standards for Phytosanitary Measures (ISPMs) are prepared by the Secretariat of the IPPC as part of the United Nations Food and Agriculture Organization's global programme of policy and technical assistance in plant quarantine. This programme makes these standards, guidelines, and recommendations available to FAO Members and other interested parties so as to achieve international harmonization of phytosanitary measures, with the aim of facilitating trade and avoid the use of unjustifiable measures as barriers to trade. Quarantine pests are of particular importance to international agricultural trade. IPPC (1997) defines a quarantine pests as "a pest of potential economic importance to the area endangered thereby and not yet present there, or present but not widely distributed and being officially controlled".

1.3 International trade of fruits

Fruits are important crops for food security and human nutrition. Fruits consumption can help prevent a wide range of diseases (Yao *et al.*, 2004; Potter, 2005; Szajdek and Borowska, 2008). Fruits supply vitamins and minerals to the diet and protect populations from diseases (Slavin and Lloyd, 2012; Lim et al., 2012; Bellavia *et al.,* 2013; Hung *et al.,* 2004; Dauchet *et al.,* 2006). The demand for fresh fruits has been increasing (Weinberger and Lumpkin, 2007) and this has led to an increase of global production of tropical fresh fruits from 12.5 million tons in 1994 to 22.1 million tons in 2013 (FAOSTAT).

Trade in fruit and vegetable products has been among the most dynamic areas of international agricultural trade, which is stimulated by rising incomes and growing consumer interest in product variety, freshness, convenience, and year-round availability. Advances in production, postharvest handling, processing, and logistical technologies, along with increased levels of international investment—have been instrumental. For developing countries, trade in fruits and vegetables has been attractive in the face of highly volatile or declining long-term trends in the prices for many traditional export products. Although many developing-country suppliers have entered the field, relatively few have achieved significant, sustained success, which means that the industry is highly competitive and rapidly changing. Despite the increase in demand and production, much of the world's population, however, does not consume the recommended five servings of fruits and vegetables daily. Potential increase in fruits production is still constrained by abiotic and biotic stresses such as fruit flies. Most fruit flies are of quarantine importance and jeopardise movement fruits trade globally.

1.4 Fruit flies (Diptera: Tephritidae) as a constraint to international fruits trade

True fruit flies", also known as Tephritid flies, are picture-winged flies of variable sizes and shapes and have a worldwide distribution (De Meyer, 2001). They are called "true" fruit flies to differentiate them from Drosophila spp., which are commonly found on rotting fruits and other foodstuffs. Tephritid flies spend part of their life cycle in a fruit, while Drosophilaspp simply feed on rotting fruits.

The currently acknowledged classification of fruit flies was presented by Norrbom *et al.* (1999) who divide the family Tephritidae into three sub families; Phytalmiinae Tephritinae and Trypetinae. The sub family Trypatinae is divided into different tribes including Adramini, Ortalotrypetini, Rivelliomimini, Toxotrypsnini, Carpomyini, Zaceratini, Trypetini and Dacini. The Afrotropical species belong to the tribe Dacini which is divided into three sub tribes; Ceratitidina, Dacina and Gastrozonina. The sub tribe Dacina includes Bactrocera and Dacus while Ceratitidina includes Capparimyia, Tririthrum and Ceratitis.

Fruit flies (Tephritid flies) are pests of quarantine importance. Some attack fruits and others attack grasses. The general biology of fruit flies is well known. The larvae of the fly develop and feed inside a fruit and cause high losses in quantity and quality. (White and Elson-Harris, 1992). Strong quarantine measures are therefore enforced against fruit flies to prevent their spread. Exporting fruit flies infested fruits could result into losses of international markets and losses of goodwill in trade. Fruit flies are important in quarantine because the distribution of major pest genera is geographically limited. According to White and Elson-Harris (1992), the Family Tephritidae is represented in all regions of the world except Antarctica. The major pest genera are nevertheless restricted to particular geographical regions as presented by White and Elson-Harris (1992). Anastrepha spp. attacks a wide range of fruits in South and Central America and West Indies. The genus Rhagoletis is found in South and Central America. Bactrocera spp. is native to tropical Asia, and the South Pacific regions with a few species found in Africa.

The genus Ceratitis is known to be of Afrotropical origin while the genus Dacus is also represented in the Afrotropical region with a few species in the Oriental region. The Afrotropical region which comprises of Africa south of the Sahara has also been invaded by several Bactrocera species. The various sub-genera of Ceratitis have been revised by De Meyer (1996; 1998a; 1998b; 2000b), De Meyer and Copeland (2001) and De Meyer and Freidberg (2005); whereas the genera Dacus and Bactrocera have been revised by White (2006).

2.0 The role of research in facilitating international trade: The case of fruits and fruit flies

2.1 Fruit flies research at SUA

Fruit flies research at SUA started in 2004, in collaboration with the Royal Museum for Central Africa (RMCA) of Tervuren, Belgium. The research was undertaken in two phases from 2004 – 2008, and from 2009 – 2013. Limited research on fruit flies was previously conducted in some parts of Tanzania (see also Mwatawala *et al.,* 2005) under the African Fruit Flies Initiative (AFFI) that was initiated by the then International Centre for Insect Physiology and Ecology (ICIPE) (Mwatawala, 2016). The SUA- RMCA research in Tanzania was concentrated in Morogoro region and focused on biology and ecology of major pest species. The second part focused on developing an Integrated Management (IPM) of key fruit fly species (Mwatawala *et al.,* 2009b). Later, the IPM project was extended to Mozambique. SUA also participated in the project on resolution of cryptic species to facilitate Sterile Insect Technique (SIT) which was supported and coordinated by the International Atomic Energy Agency (IAEA) based in Vienna, Austria. Further research on fruit flies was conducted under the project on “Increasing Value of African Mango and Cashew” in collaboration with Aarhus University, Denmark. SUA has published more than 20 articles on fruit flies, a book chapter, one management plan and an extension manual and a TV program. SUA also organises an international training course on fruit fly taxonomy and ecology, in collaboration with RMCA.

The research at SUA in collaboration with global partners provided very important information which is necessary for facilitating fruits trade through Pest Risk Analysis (PRA). PRA is a process of evaluating biological or other scientific and economic evidence to determine whether or not a pest should be regulated and what phytosanitary measures should be taken against it (IPPC, 1997). PRA is conducted to minimise risks of introduction of pests through movement of fruits. The first step of PRA is categorisation of a pest as quarantine or non–quarantine. Identity and the presence in an area is a key to the categorisation of a quarantine pest. Our research established the biodiversity of fruit flies in Eastern Central Tanzania (Mwatawala *et al.,* 2006a) and has contributed to this important PRA step through the detection of exotic pest species, resolving identity of cryptic species and the description of new pest species. These are highlighted in the sections that follow.

Image 1: Major fruit fly pests in Tanzania (clockwise from top left) B. dorsalis, C. rosa, C. cosyra and C. captata

2.2 Detection of invasions

Various Tephritid species have been accidentally or intentionally introduced into the areas beyond their natural range. For example, *Bactrocera carambolae* is native to the Oriental Region, but was introduced to Surinam, French Guyana, Guyana and northern Brazil (Amapá) (Sauers-Muller, 1991; Drew and Hancock 1994). *Zuegodacus cucurbitae* (Coquillett), which is probably native to the Oriental Region, has been introduced into East Africa, Mauritius, the Ryukyu Islands of Japan, New Guinea and the nearby islands, Guam and Hawaii (Munro, 1984; Hooper and Drew 1989; Kakinohana, 1994). *Bactrocera dorsalis* (Hendel) which is native to the Oriental Region, has been introduced into Hawaii, Guam, Nauru, and Mauritius and Africa. *Ceratitis capitata* (Widemann) is native to tropical Africa, but was introduced to the Mediterranean area, Southern Africa, various islands of the Atlantic and Indian Oceans, Western Australia, Hawaii, Central America, and much of South America (De Meyer, 2000). Dacus ciliatus (Loew), which is native to Africa, has been introduced to the Middle East, southern Asia east of Burma, and to Mauritius (White and Elson-Harris, 1992) (See also Norrbomet *et al.* 1998). Such introductions are an increasing threat of the spread of this pest species, due to a worldwide increase of both commodity shipments (including fresh fruits from other continents) and the booming intercontinental tourism industry. For example, the introduction and presence of the peach Fruit Fly *Bactrocera zonata* (Saunders) in Egypt and Mauritius, is linked to the movement of infested fruits by human activities and not by natural dispersal. Fruit fly invasions have huge impacts to the horticulture industry (Mwatawala , 2008)

2.2.1 Detection of the Oriental fruit fly Bactrocera dorsalis (Hendel) (formerly Bactrocera invadens Drew Tsuruta& White) in Tanzania

In 2004, we sampled mango from Matombo Ward, Mvomero District, in Morogoro Region from which a total of 30 adult flies emerged. The specimens were taken to the RMCA for training on identification of Afrotropical fruit fly species. We noted that four individuals in the sample were morphologically different and resembled species native to Asia (Mwatawala *et al.,* 2004). The specimens were sent to Dr. Ian M. White of The Natural History Museum, London, UK and Prof. Richard Drew of Griffith University, Australia both of these confirmed that the species was "new to science" and had been detected for the first time in Kenya in 2003. This Tanzanian record was the second (Mwatawala *et al.,* 2004). The species was later described and named as Bactrocera invadens Drew Tsuruta & White under a common name of the African invader fly. The presence of this species resulted into losses of markets of African fruits, particularly banana Musa sp., mango (Mangifera indica L.) and avocado (Persea americana Miller). Strong quarantine measures against the pest were imposed to prevent spread and introduction of the species into other countries. However, the identity of this species was later disputed, as will be shown in the subsequent sections of this lecture.

2.2.2 Detection of the solanum fruit fly Bactrocera latifrons (Hendel) in 2006

We monitored the population of fruit flies at the Horticulture Unit, SUA Main campus in Morogoro, from 2004 to 2013. In June 2006, we noted two specimens that were morphologically similar to Bactrocera dorsalis but with some variations in the abdominal colour pattern (Mwatawala *et al.,* 2006). We suspected that the specimens were not B. invadens. We sent the specimens to the experts of Bactrocera taxonomy for identification, who found that the species was Bactrocera latifrons (Hendel), a native of Asia, which had never been recorded before in Africa (Mwatawala *et al.,* 2007). The pest was later recorded in neighbouring Kenya. Bactrocera latifrons is of quarantine importance, although restricted to a few families, mainly Solanaceae. The impact of the pest was never felt in East Africa because fresh Solanaceae were not among the major export crops from the region.

2. 3 Resolving identity of cryptic species and description of new pest species

The case of the Oriental fruit fly *B. dorsalis*

The African invader fly *B. invadens* was thought to be new to science after its detection in Kenya and later in Tanzania (Mwatawala *et al.,* 2004). However, there were two schools of taxonomic thoughts: one school regarded this species as "new to science" and was properly named *B. invadens*. The other school of thought held that this species was actually the Oriental fruit fly Bactrocera dorsalis (Hendel), a serious pest of fruits native to Asia. Studies which were coordinated by the International Atomic Energy Agency (IAEA) revealed a considerable body of evidence spanning from morphological, molecular, cytogenetic, sexual compatibility and chemo-ecological data to reject the current taxonomy of B. invadens as a species distinct from B. dorsalis (Schutze *et al.,* 2014). The existing morphological diagnostic characters, particularly aedeagus length and postsutural lateral vittae, vary continuously across *B. dorsalis* and *B. invadens* geographic distributions (Schutze *et al.,* 2014). Scutum colour is highly variable across Africa and the Indian subcontinent but becomes predominantly black in populations of East and South-east Asia. This means that African markets in Asia and Hawaii were opened because the pest was already present. Furthermore, a wealthy of literature which is available in Asia would be optimised for African situation.

2.3.1 The case of Natal fruit fly Ceratitis rosaKarsch and Ceratitis quilici De Mayer Mwatawala &Virgilio

The Natal fruit fly *C. rosa* is a quarantine fruit fly species which is indigenous to Africa. Studies in South Africa showed that the species is adopted to warmer climates, and this implies that chances of establishment in temperate countries are low. Studies in Re-union showed that *C. rosa* is adopted to cooler climates, which contradicts the South African findings. We sampled *C. rosa* along an altitudinal transect on the Uluguru mountain and found that the species occurred in substantial numbers along the transect (Mwatawala *et al.,* 2006a; 2006b; Geurts *et al.,* 2012; Geurts *et al.,* 2014; Mwatawala *et al.,* 2015). The important question is why is the species adapted across a range of climates and hosts? A study by Virgilio *et al.* (2013) recognized five microsatellite genotypic clusters within the FAR complex, two of which correspond with *Ceratitisrosa*. Further studies including morphometrics, developmental physiology, cuticular hydrocarbons, pheromones and mating incompatibility (De Meyer *et al.* 2015) provide evidence that these two genotypic clusters represent two distinct entities that should be considered as separate species. *Ceratitis rosa* was later determined as a species adapted to low altitude, warm, and humid areas. The other species was new to science and was identified as Ceratitis quilici De Meyer, Mwatawala &Virgilio (De Meyer *et al.,* 2016). This species is adapted to high altitudes and cold areas.

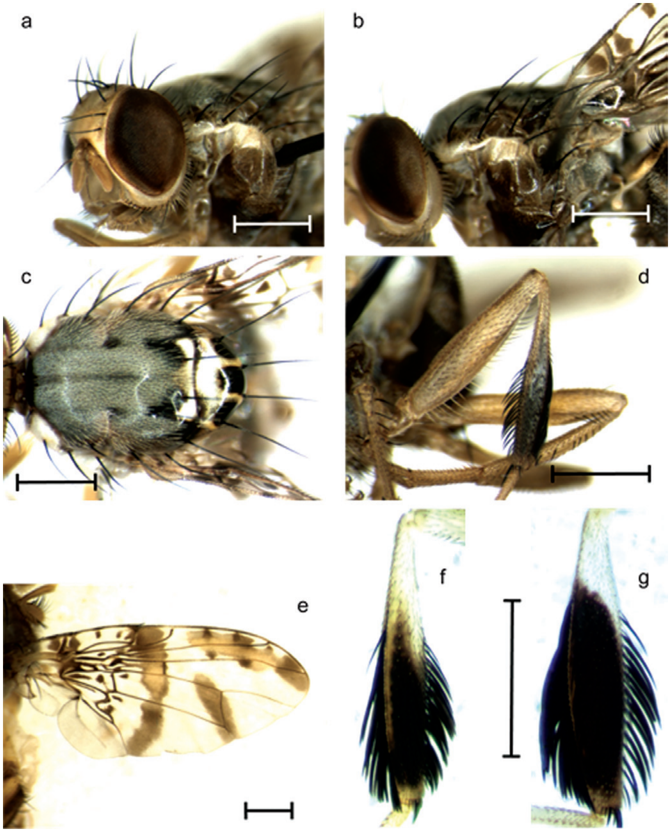

Image 2: Ceratitis qulici showing various parts of the body (source: De Meyer *et al.,* 2016*)*

2.3.2 The case of mango fruit fly *Ceratitis cosyra* (Walker) and *C. pallidula* De Meyer Mwatawala & Virgilio

The mango fruit fly *Ceratitis cosyra* is another indigenous pest of quarantine importance. While sampling using terpinyl acetate and later using enriched ginger oil (EGOlure, Insect Science, Tzaneen South Africa) we noted that the flies which were found in traps were smaller compared to *C. cosyra* (Mwatawala *et al.,* 2012a; 2012b; 2015). We suspected that this was a species which was different from *C. cosyra*. We later resolved that the species is similar to *C. cosyra* but can readily be differentiated by the absence of a black spot on the postpronotal lobe and the much smaller size. The species was then described as Ceratitis pallidula De Meyer Mwatawala & Virgilio (De Meyer *et al.,* 2016)

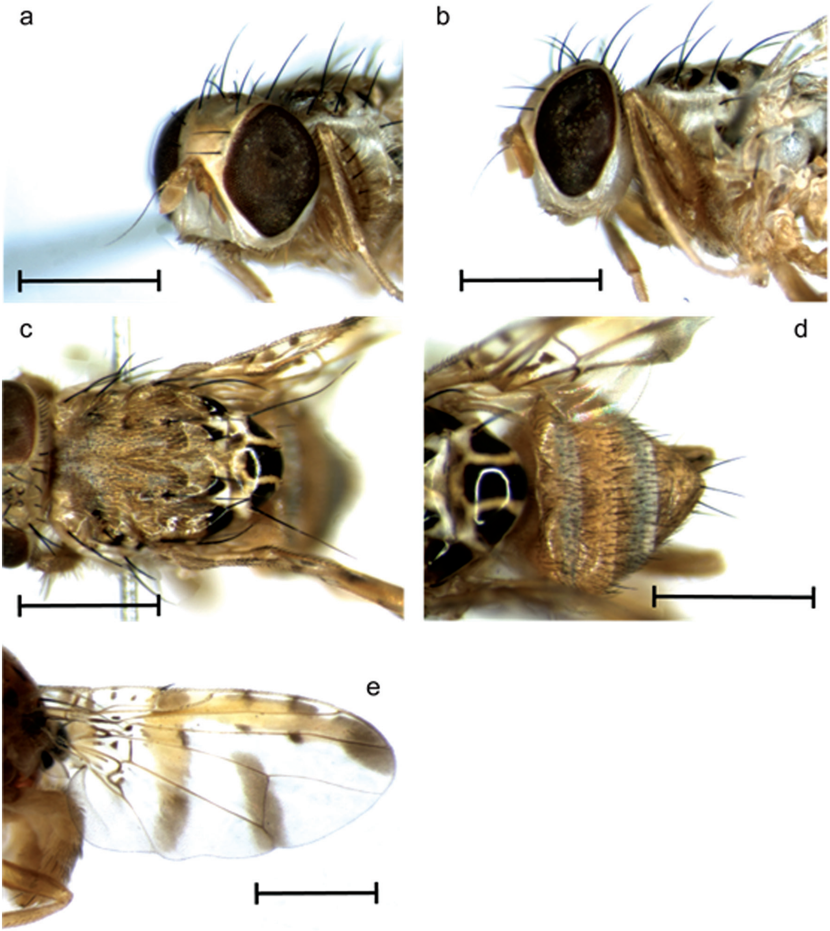

Image 3: Ceratitis pallidula showing various parts of the body (source: De Meyer *et al.*, 2016)

2.3.4 The case of Phyllonorycter mwatawalai De Prins

Our IPM project against fruit flies included surveys for micro lepidopidipta moths as potential pests of mango. Surveys were conducted in both cultivated orchards and wild growing mango trees where we recorded several new species; among them was *Phyllonorycter mwatawalai* De Prins a moth of the Gracillariidae family. This was found in the Morogoro area of Tanzania in a degraded savannah-like habitat, a natural biotope rich in low-growing woody Acacia trees and bushes and thick low dry herbacious vegetation. The pest status of the species is still unknown (De Prins and Kawahara, 2012).

2.4 Determining the Probability of entry, establishment of spread of fruit flies

2.4.1 Host range and preference of fruit flies

Entry, establishment, and the spread of a pest depend on the availability of hosts and favourable climate. The availability of preferred hosts in a PRA area determines the success of entry and establishment of an exotic pest. Preference is the set of likelihoods of accepting a particular host (Singer, 1986). First of all, host preference takes into consideration the sum of plants that are hosts to an insect species (host range) as well as how acceptable and/or suitable these hosts are relative to each other (host specificity). Thus, when two hosts are available in equal abundance, the one that is attacked with a high infestation rate is the preferred host. Suitability of a host, which is a key factor of guiding insect choice, depends upon a number of factors such as nutritional quality, host plant defence chemicals, prevalence of natural enemies or microenvironment (Thompson *et al.,* 1991). According to preference-performance hypothesis (optimal oviposition theory), females are assumed to maximize their fitness by ovipositing on high quality hosts. Females visit host plants mainly to oviposit. Thus, the selection of host species and the fruit type for larvae is pre-determined by the egg-laying females. Therefore, a female chooses the best possible host plant on which to oviposit and for her offspring to develop, in other words, “mother knows best” (Prager *et al.,* 2014). See also Mkiga *et al.* (2015) and Mwatawala *et al.* (2010a).

We sampled fruits in Tanzania to determine their host status to fruit flies (Mwatawala *et al.,* 2006a; 2006b; 2009c). We found positive samples from 35 different plants from 14 different families. *Bactrocera dorsalis* had the largest host range (27 species, 12 families) (Mwatawala *et al.,* 2009c). This study added new host species of *B. dorsalis* that included *pomeloCitrus* grandis (Burman Merr.), Coffee (*Coffea canephora* Pierre ex A. Froener), apple (*Malus domestica* Borkh.), strawberry, guava (*Psidium littorale* Raddi) African eggplant (*Solanum aethiopicum* L.), lucky nut (*Thevetia peruviana* (Pers.) and Schumann) and jambolan (*Syzigium cumini* (L.) Skeels) bringing the total number of reported hosts to 37. Host range of the other main fruit fly species ranged from 6 to 19.

The host range of the major fruit fly species was different with respect to plant families except *B. cucurbitae*, which was recorded mainly from *Cucurbitaceae*. *Ceratitis cosyra* showed predominance for *Annonaceae* and *Anacardiaceae* species (Mwatawala *et al.,* 2009c).

Of interest were two controversial hosts of *B. dorsalis*; banana (Musa sp.) and avocado (*Persea americana* L.). Previous studies never agreed on the host status of avocado to fruit flies. Sampling results from Tanzania showed that avocado was attacked by *B. dorsalis*, albeit at low rate of incidences (Mwatawala *et al.,* 2009c). Studies showed that avocado (Hass variety) is a poor potential host for other fruit fly species *C. capitata* and *C. cosyra* (De Graaf, 2009). We did not find any positive sample of banana. It was later resolved that green banana cannot be attacked by fruit flies. Only ripe, thin skinned and which are often split can be attacked by fruit flies (see also Cugala *et al.* 2013). The markets of banana and avocado lost to South African markets which were then opened.

We also sampled suspected hosts of B. latifrons (Mwtawala et al., 2010b; Mziray *et al.,* 2010) Twelve solanaceous fruit species yielded *B. latifrons* of which four are new host records: *Capsicum annuum* L. cov. longum A. DC., Capsicum chinense Jacq., Solanum sodomeum L., and Solanum scabrum Mill. Similarly, three *cucurbitaceous* fruit species provided positive rearings and these are also new host records: watermelon *Citrullus lanatus* (Thunb.) Matsum & Nakai, *Cucumis dipsaceus* L., and *Momordica trifoliata* L. The infestation rate and incidence of the pest was mainly high in the solanaceous hosts of nightshades (*Solanum nigrum* L. and *Solanum scabrum*) and African eggplants (*Solanum aethiopicum* Lam. and *Solanum anguivi*). In a host preference study involving limited number of cultivated solanaceous crops, *S. scabrum* was recorded as the most preferred host (Mziray *et al.,* 2010).

2.4.2 Spatial and temporal distribution of major fruit flies

The basic processes which determine the population size of a species at any given time are four, namely, Immigration, birth, migration and death. Furthermore population is also determined by intra and inter specific competition, predation (by parasitoids, true predators, parasites and pathogens). Human activities notably management practices such as pesticide application, crop rotation, mixed cropping and trade also determine population size of pests. Furthermore, pest species adopt a set of life strategies of dealing with a life threatening problem. These strategies include age at which reproduction begins, relative energetic efforts devoted to reproduction, growth, survivorship and predator avoidance; diversion of energy to migration and dispersal. In nature, there are two groups of individuals; r - selected species whose population sizes fluctuate widely, they live in unpredictable environment, have unpredictable mortality rates, they mature early, are smaller in size and have shorter life span. The k – selected species these have relatively stable populations, they live in predictable environment, have predictable mortality rates; they mature late and have longer life span. Climate is another determinant of population fluctuation.

2.4.3 Seasonal abundance of major fruit fly pests in Eastern Central Tanzania

The temporal occurrence of the invasive and economically important pest fruit fly, *Bactrocera dorsalis* was studied in three agro-ecological areas of Morogoro Region and was found to be permanently present at low and mid-altitudes (380–520 m a.s.l.) with peak periods coinciding with the fruiting season of mango and guava (Psidium guajava) (Mwatawala *et al.,* 2006b; 2012c). Its incidence at high altitude (1650 m a.s.l.) was only temporal and was apparently the result of dispersal from lower altitudes after the mango fruiting season. The polyphagous invasive fruit fly *B. dorsalis* and the indigenous fruit fly *C. rosa* showed a similar temporal pattern, but were largely separated spatially, with *B. dorsalis* being abundant at lower elevations and *C. rosa* predominant at higher elevations (Geurts *et al.,* 2012; 2014). The abundance of *B. Invadens* was positively correlated with temperature and mango was a determining factor for *B. dorsalis* distribution (Geurts *et al.,* 2014)

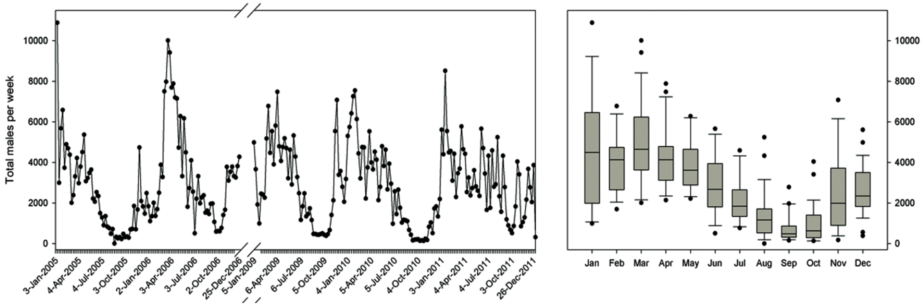

Figure 1: Temporal abundance of B. dorsalis in Morogoro

2.4.4 The spatial and temporal distribution of *B. latifrons* in Tanzania

Surveys were conducted covering the main part of Tanzania along the following axes: Coast – North Eastern zones (to the border with Kenya); Coast – South Western zone (to the border with Malawi and Zambia); Central – North Western zones (to the border with Uganda, Rwanda, Burundi and Congo). The first surveys covered the coast and the northeastern zones of Tanzania, including Dar Es Salaam (Kinondoni District), Coast (Bagamoyo), Tanga (Muheza, Lushoto and Mombo), Kilimanjaro (Hai, Moshi) and Arusha (Arusha and Arumeru). We also covered the south-western regions of Tanzania, including Mbeya (Mbeya, Rungwe and Kyela) and Iringa (Kilolo); the central and north-western regions of Tanzania, including Dodoma (Mpwapwa District), Singida (Singida and Manyoni), Tabora (Nzega and Igunga), Shinyanga (Kishapu), Kagera (Ngara, Missenyi, Bukoba, Muleba and Biharamulo) and Mwanza (Magu, Kwimba, and Misungwi) (Mwatawala *et al.,* 2010b). The routes ensured maximum coverage of the country by reaching the borders to Kenya, Malawi, Zambia, Burundi, Rwanda and Uganda. Our surveys showed that the species was widespread throughout the country but was most abundant in the north-eastern region close to the border with Kenya. The majority of the positive samples were mostly obtained from the African eggplant, *Solanum aethiopicum* (Mwatawala *et al.,* 2010b). Our studies further showed that B. latifrons is most abundant in low altitude to medium altitude areas (Mziray *et al.,* 2009).

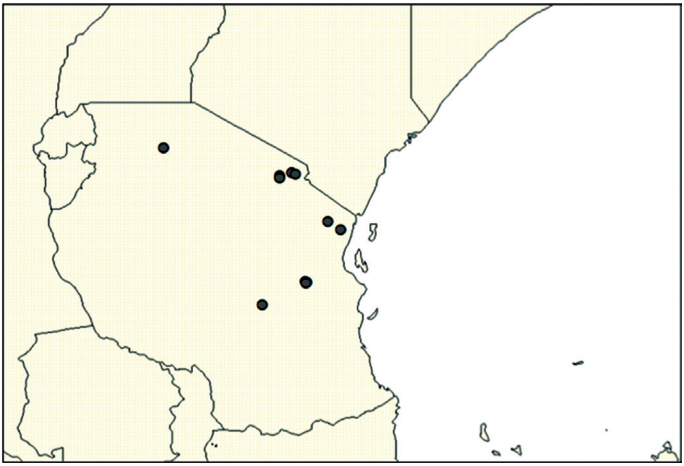

Figure 2: B. latifrons distribution in Tanzania

2.4.5 Potential distribution of *B. dorsalis* using Climex

Population of *B. dorsalis* was monitored in twenty-three sampling sites across Benin, Ghana, Kenya, Niger, Senegal, Sudan, Tanzania, and Zambia. These were monitored for two years from 2011 (De Villiers *et al.,* 2016). The locations in Tanzania included Morogoro, Korogwe, Mlingano (Tanga), Makutupora (Dodoma), Songea municipality, and Oldeani (Manyara). Seasonal phenology data, measured as fly abundance throughout the year, were related to each location's climate to infer climatic growth response parameters. These functions were used along with African distribution records and development studies to fit the niche model for *B. dorsalis*, using independent global distribution records outside Africa for model validation. We found that areas, which were at the greatest risk of invasion by *B. dorsalis* include South and Central America, Mexico, southernmost USA, parts of the Mediterranean coast, parts of Southern and Eastern Australia and New Zealand's North Island. Under irrigation, most of Africa and Australia appear climatically suitable (De Villiers *et al.,* 2016).

Image 4: Sampling sites to determine potential distribution of B. dorsalis (source:* De Villiers *et al.,* 2016*)

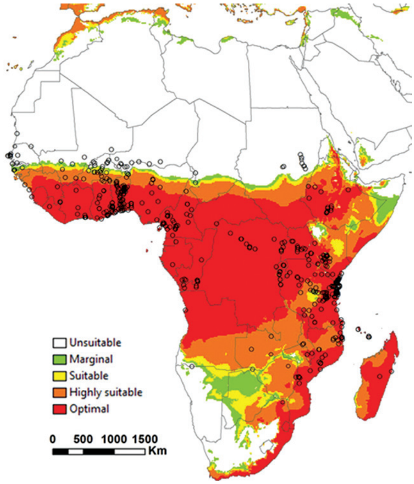

Image 5: Potential distribution of B. dorsalis in Africa (source:* De Villiers *et al., 2016)

2.5 Assessing the risks of introduction to biodiversity

According to Duyck *et al.* (2004), the presence of a newly introduced invasive polyphagous species results into competition with native species. In the absence of competition a species occupies a fundamental niche and uses a full range of resources which are needed for its growth and reproduction. The competitive interaction may result either in ecological displacement by which one or both species shifts or reduces its niche until co-existence becomes possible, or in competitive exclusion of one species.Invasive species are often said to be-selected. However, invaders must sometimes compete with related resident species. In this case, invaders should present combinations of life-history traits that give them higher competitive ability than residents even at the expense of lower colonization ability.

Our studies on temporal distribution suggested that *B. dorsalis* is an r strategist species (rapid population growth and colonization of new habitats, rapid decline in populations during unfavourable conditions, etc.) (Mwatawala *et al.,* 2006b). On the other hand, Vayssieres *et al.* (2005) suggesting that the species was a K-strategist, based mainly on its large body size. Duyck *et al* (2007) suggested that the key traits for invasion in this system were those that favoured competition rather than colonization. Our studies also hinted that B. dorsalis competitively displaced the native *C. cosyra* (Mwatawala *et al.,* 2006b; 2009a). When we compared demographic parameters of *B. dorsalis* and the native *C. cosyra* in controlled environment; our results showed that *B. dorsalis* larval and pupal development of *B. dorsalis* was significantly faster than that of *C. cosyra* independent of temperatures. Life expectancy of male *B. dorsalis* was significantly greater than that of *C. cosyra*; whereas life expectancy of female *B. invadens* was greater, though not significant, than that of *C. Cosyra*. The average net fecundity was higher for *B. dorsalis* than was for *C. cosyra*. Both species attained their highest intrinsic rate of increase and net reproductive rate at 30°C; *B.invadens* exhibited the highest intrinsic rate of increase and net reproductive rate at all temperatures tested than did *C. Cosyra* (Salum *et al.,* 2013). These results provided further evidence that *B. dorsalis* is both a good competitor and coloniser. We further provided ecvdence of competitive displacement of *C. cosyra* by *B. dorsalis*.

2.6 Mitigation of the risks posed by new introductions

2.6.1 Integrated Pest Management (IPM) in Eastern Central Tanzania

According to Aluja (1996), any designed IPM program for managing fruit flies should be viewed as a transition from a chemical dependent control to an ecological model pest management. Natural products such as neem should be researched on their ability to reduce populations of fruit flies. In this regard, a study by Verghese *et al.* (2006) included a neem-based product, Azadirachtin, in their IPM program for *B. dorsalis*. Botanical insecticides such as neem are safer to use and are compatible with organic farming. Many new tools and approaches recently developed may be very effective in controlling the fruit fly problem; but whether these tools are compatible with the entire crop production scheme in respect to cost effectiveness is rarely considered (Aluja, 1996). Botanical pesticides and less toxic synthetic pesticides and those with promising results should be recommended to farmers. What should be done at this stage is to adopt a control program from other areas for testing and refining until they are suitable for use in our farming systems. Programs such as initiated by Verghese *et al.* (2004; 2006) can be adopted and proposed to farmers while ecologically based pest management systems, which are compatible with the Tanzanian farmer situation are being designed (Mwatawala *et al.,* 2009a).

We compared spot application of molasses bait with broadcast sprays of insecticide dimethoate/lambda cyhalothrin (Karate5 EC) and spot application of a spinosad bait (Success, Dow AgroSciences) plus mass trapping using methyl eugenol, as components of IPM programs for *B. dorsalis*. Orchard sanitation and early harvesting of fruits were standard practices in each program (Mwatawala *et al.,* 2015). We did not record significant differences amongst the three IPM treatments which were evaluated with respect to reductions in the incidence and infestation rates of *B. dorsalis* in mango (Mwatawala *et al.,* 2015; Mwatawala, 2016). However, the cost-benefit analysis gave positive Cost Benefit Ratios (CBRs) for the molasses bait-based IPM and the insecticide spray-based IPM but not for the IPM based on the GF 120®/ SUCCESS® bait (i.e. spinosad). IPM based on the molasses bait was ranked the highest in delivering farmers the greatest benefits in terms of CBR, environmental protection and consumer health. Spinosad-based IPM had a low CBR because of its limited availability, high price and high frequency of application compared to conventional insecticides (Mwatawala *et al.,* 2015; Mwatawala, 2016). The developed IPM program was later optimised and tested against B. dorsalis in Manica Province, Mozambique and the results are yet to be published.

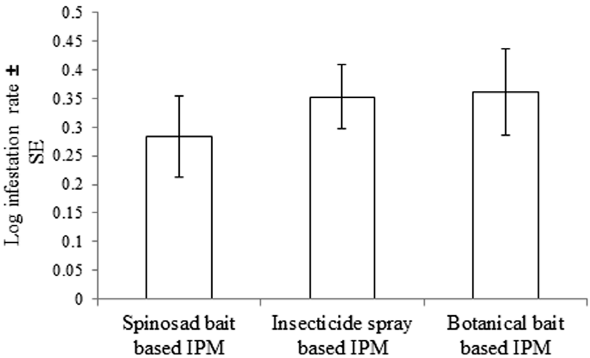

Figure 3: Infestation rate of B. dorsalis in mango

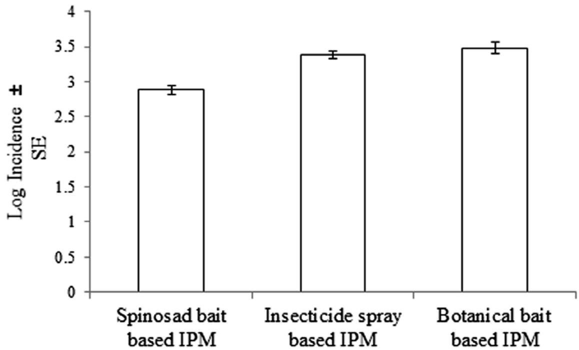

Figure 4: Incidence of B. Dosalis in mango

2.6.2 Controlling fruit flies using weaver ants Oecophylla longinoda Latreiila (Hymenoptera: Formicidae)

SUA and Aarhus University (Denmark) collaborated in a research programme to increase the economic value of African mango and cashew. We studied the efficacy of weaver ants, *O. longinoda*, in controlling fruit flies in mango. Three treatments were compared: (i) trees protected by *O. longinoda* (ii) trees protected by the insecticide spray, Dudumida® (70WG imidacloprid, Mega

Generics Ltd., Tanzania) and (iii) unprotected trees (control) (Mwatawala, 2016; Abdulla *et al.,* 2017). Overall, the incidence (percentage of infested samples) and the infestation rate (number of emerged adult flies per unit weight of fruits) of fruit flies were significantly lower on both the *O. longinoda* and the Dudumida-protected trees compared with the control. Although the lowest incidence of fruit flies was recorded in fruits from the *O. longinoda* treatments, there was no significant difference in incidence or infestation rate between the *O. longinoda* and Dudumida (Mwatawala, 206; Abdulla *et al.,* 2017).

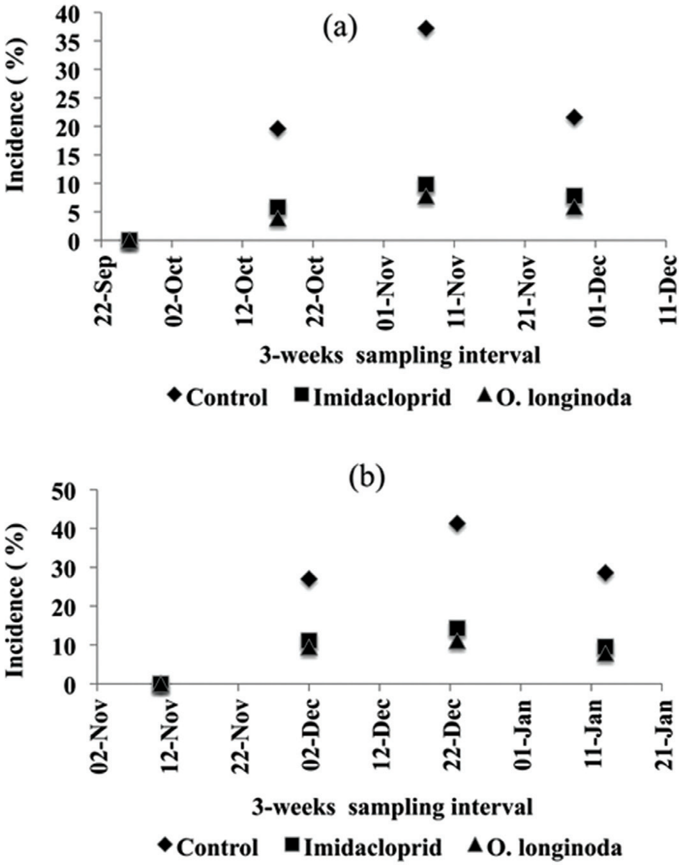

Figure 5: Incidence of B. dorsalis in mango
***(Source:** Abdulla *et al.,* 2017).

Colonies of *Oecophyllas* pp. can be transplanted from wild habitats into orchards. The transplanted colonies can only survive in the presence of egg laying queens. It is difficult to locate the nests with egg laying queens in large colonies that may sometimes contain more than 100 nests. Our studies developed an efficient method of locating a nest with a queen in a colony (Nene *et al.,* 2017). We also explored and developed methods for rearing newly mated queens in nurseries. At first, little was known about the mating behavior of *O. longinoda,* particularly the timing of nuptial flights. We found that sexuals of weaver ants aggregated on the nest surfaces prior to the flights. We also found that flights took place during the rainy season, and mostly in the evenings just before sunset. (Nene *et al.,* 2015). The days of flights were associated with higher relative humidity and less sunshine; the flights mainly took place around full moons. We also investigated four methods which may be used to collect mated queens that can subsequently be used to stock ant nurseries. We found that light trapping was the most efficient way of collecting queens followed by leaf traps, random search, and lastly paper traps (Rwegasira *et al.,* 2014). We also observed that queens were best reared under continuous, indirect access to water. Rearing mated queens under continuous indirect access and continuous direct access to water methods saved energy and time, because of limited attendance to the colonies (Rwegasira *et al.,* 2015). Availability of water, sugar solution, and different sources of protein throughout improved the growth of young colonies.

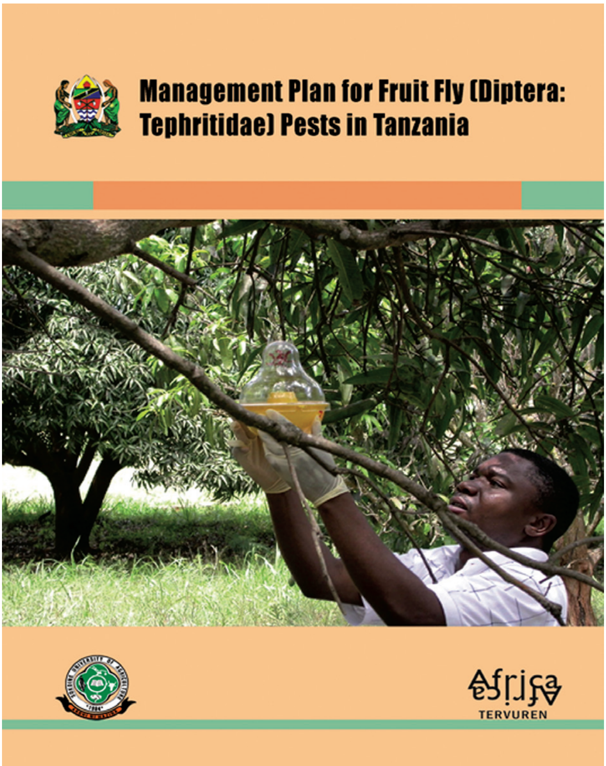

Image 6: Management plan of fruit flies in Tanzania

2.6.3 Management plan for fruit flies in Tanzania

Future plan for fruit fly management in Tanzania proposes an Area Wide Programme to extend research and implementation of IPM to other parts of the country (Mwatawala *et al.* 2013). The objectives of this management plan include (i) establishing the nationwide status of economically important fruit flies (ii) assessing the nationwide economic impact of fruit flies on the horticultural industry (iii) evaluating the available mechanisms for fruit fly control (iv) formulating management programmes for mitigation of fruit fly problems in horticulture nationwide, and (v) re-enforcing long term awareness, capacity building and collaboration. The government of Tanzania and its research institutions are actively looking for funds to finance these activities (Mwatawala *et al.,* 2013).

2.6.4 Training programs

SUA and RMCA organise a training course in taxonomy and systematics of African fruit flies at the Sokoine Pest Management Centre. The objective of this group training is to offer basic training on the identification and ecology of African fruit flies that have an economic impact on agriculture. The course consists of topics on morphology, classification, identification, identification methods, collection methods, and conservation methods.

3.0 Conclusion

This inaugural lecture highlighted key research findings on fruit flies based on studies conducted at SUA in collaboration with other partners. The information that was generated by years of research is necessary to facilitate fruits trade while minimising the risks of the spread of fruit flies. The lecture showed further that this information is shared through various means including an international training on taxonomy and ecology of fruit flies.

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