SYSTEMS APPROACH FRAMEWORK FOR INTEGRATED ARTHROPOD PEST MANAGEMENT IN SMALLHOLDER TOMATO (*Solanum lycopersicum*) PRODUCTION IN KENYA

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DECLARATION

This thesis is my original work and it has not been presented for award of degree in any other university

19th November, 2019

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DEDICATION

This thesis is dedicated to my wife Beryl, my son Mich, and to my late parents Caroline and Delphan Ochilo

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ACRONYMS AND ABBREVIATIONS

AAK	Agrochemicals Association of Kenya
AEZs	Agro-ecological zones
AGRA	Alliance for a Green Revolution in Africa
AI	Active ingredient
AIS	Agricultural Innovation Systems
AKIS	Agricultural Knowledge and Information Systems
ANOVA	Analysis of variance
AT	Action threshold
CABI	Centre for Agriculture and Bioscience International
CAN	Calcium Ammonium Nitrate
CBOs	Community Based Organizations
CI	Confidence interval
DDT	Dichlorodiphenyltrichloroethane
DFID	Department for International Development
DGIS	Directorate-General for International Cooperation
DSP	Double Super Phosphate
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GDP	Gross domestic product
GoK	Government of Kenya
HCD	Horticultural Crops Directorate
HHP	Highly hazardous pesticide
IAPM	Integrated Arthropod Pest Management
ICM	Integrated crop management
IPM	Integrated pest management
KALRO	Kenya Agricultural and Livestock Research Organization
KENDAT	Kenya Network for Dissemination of Agricultural Technologies
KEPHIS	Kenya Plant Health Inspectorate Services
KES	Kenyan shilling
KNBS	Kenya National Bureau of Statistics
LH	Lower highland zones
LM	Lower midland zones
LSD	Least significant difference
MoALF	Ministry of Agriculture, Livestock and Fisheries
NDV	National data validation
NEPAD	The New Partnership for Africa's Development
NGOs	Non-Governmental Organizations
OECD	Organization for Economic Cooperation and Development
PI	Proportion of units infested
POMS	Plantwise Online Management System
POPs	Persistent organic pollutant
RCBD	Randomised complete block design

RSA	Research Solutions Africa Limited
SDC	Swiss Agency for Development and Cooperation
SEM	Standard error of the mean
SPSS	Statistical Package for the Social Sciences
SRC	Secretariat of the Rotterdam Convention
TA	Tropical Alpine zones
TT	Tally threshold
UH	Upper Highland zones
UK	United Kingdom
UM	Upper Midland zones
UNEP	United Nations Environment Programme
UON	University of Nairobi
USDA	United States Department of Agriculture
YFL	Young-fully-opened leaflets

ABSTRACT

Arthropod pests have emerged as a major constraint in smallholder tomato (*Solanum lycopersicum* L) production in Kenya. For their management, the focus of crop protection research has been the curative control of the pests. Whilst such focus has contributed immensely to enhanced agricultural production, the indiscriminate use of chemical products has created new problems, including the negative effects of pesticides on public health, food safety and the environment. To complement entirely curative – and occasionally technology-driven – interventions, a 'systems approach' to pest management innovation is being suggested. The objective of this study, therefore, was to develop a systems approach framework for integrated arthropod pest management (IAPM) in the smallholder tomato production system in Kenya. The Plantwise programme – an innovative approach to support the delivery of agricultural extension service, and an experimental research, are both used to study tomato production system in Kenya. The study investigated the pest problem at three levels: plant/crop, farm and farm household. The primary aim of this approach was to address knowledge gaps in the fields of crop protection, ecology, and socio-economics. The study finds that any sustainable approach towards the management of arthropod pests must contend with the broadly categorised 'big five dilemmas': (1) *farmers' circumstances (resources and constraints)* - decline in area under tomato cultivation, minimal adoption by farmers of high-yielding varieties, farmers grappling with other biotic pests (besides arthropod pests) and abiotic constraints, and gender inequality in the production system; (2) *the pest problem* - a diverse range of arthropod pests hamper smallholder tomato production in Kenya; key among them being tomato leafminer, whiteflies and spider mites; (3) d*ecision-making by farmers and agricultural extension agents* – limited adoption of IPM technologies by farmers and agricultural extension agents; (4) *Pesticide use* – increased usage of synthetic pesticides, including highly hazardous pesticides; and (5) d*ecision support tools usage* – opportunities exist for the uptake of a wide range of tools geared towards supporting participatory processes and decision analysis by farmers. The findings of this study underscore the need to design dynamic approaches to IAPM that take into account the highlighted complexities of agroecosystems and the diversity of farming circumstances, and that such approaches strengthen practitioners' capacity to adapt crop protection to local realities.

CHAPTER 1
INTRODUCTION

1.1 Background information

Tomato (*Solanum lycopersicum* L), a popular and extensively cultivated vegetable, is among the promising commodities in horticultural production in Kenya. The food crop belongs to the family Solanaceae, a medium-sized angiosperm family consisting of approximately 100 genera and 3,000 – 4,000 species (Knapp et al., 2004, Oduor, 2016). In Kenya, tomato is eaten by nearly all of the households as a source of vital nutrients, including vitamin C, flavonoid compounds (kaempferol, quercetin, naringenin, rutin and myricetin), carotenoids (β-carotene and lycopene) and phenolic acids (gallic and chlorogenic acids) – all of which have antioxidant capacity (Sainju et al., 2003, Saunyama and Knapp, 2003, Knapp et al., 2004, Hallmann, 2012). In terms of production, Kenya is amongst the leading lights in sub-Saharan Africa producing 410,033 tonnes of the produce (FAO, 2018). Additionally, the crop constitutes 7% of the total horticultural produce in the country and 14% of the entire vegetable produce (Geoffrey et al., 2014).

Over the years, tomato production in Kenya has intensified (FAO, 2018). Yields, however, have remained low (Table 1). The main constraints hindering tomato production can be categorized into three, namely agronomic, institutional and market constraints (Asgedom et al., 2011). Lack of access to markets, coupled with fluctuating commodity prices, has been identified as a major constraint to smallholder tomato production (Clottey et al., 2009, Asgedom et al., 2011). Moreover, small - and medium – scale commercial farmers also contend with a number of institutional challenges which include; limited access to inputs, lack of improved varieties, lack of transportation and lack of storage facilities (Asgedom et al., 2011). On the other hand, key agronomic challenges faced in tomato production include incidences of pests, diseases and physiological disorders (caused by non-pathological conditions such as drought, cold, heat and salinity) (Umeh et al., 2002, Anastacia et al., 2011, Asgedom et al., 2011, Toroitich et al., 2014, Oduor, 2016).

Tomato is generally attacked by many minor pests and few major pests (Nault and Speese Iii, 2002). Overtime, the focus of crop protection research has been the curative control of pests (Schut et al., 2014). This focus has mostly been mono-disciplinary oriented with innovation generally equated with the development and adoption of individual-component technologies such as new agro-chemicals (Schut et al., 2014). Whilst such focus has contributed immensely to enhanced agricultural production, the indiscriminate use of chemical products, for instance, has created new problems, including the negative effects of chemical products on public health, food-safety and the environment (Asante et al., 2013, Schut et al., 2014). Also, it has led to the development of pest resistant populations in crop production systems and a decline in availability of active substances (Barzman et al., 2015, Mahmood et al., 2016).

Table 1: Production of tomato, 2013 - 2016

Year	Production (000' tonnes)	Gross production value (current million US$)
2013	494.0	319.7
2014	443.3	319.6
2015	402.5	252.4
2016	410.0	248.1

Source: FAOSTAT

To complement entirely curative – and occasionally technology-driven – interventions, Rodenburg et al. (2015) advocates for a systems approach to pest management innovation. A systems approach to pest management considers a particular crop protection challenge not just on the basis of a crop - pest interaction but also considers the context within which the pest occurs (Rodenburg et al., 2015). By implication, it considers socio-economic and biophysical processes and the informal and formal institutions governing the sector (e.g. regulations and policies). Furthermore, it considers the interests of multiple stakeholders (e.g. farmers, extension agents, agro-input dealers and policy makers) (Rodenburg et al., 2015).

According to Rodenburg et al. (2015), the need for a systems approach to pest management is supported by the hypothesis that a pest problem at the crop level cannot be addressed unless a conducive environment is created for managing the pest outbreak. Despite the aforementioned benefits, systems-oriented approaches to crop protection problems remain scarce (Schut et al., 2014, Rodenburg et al., 2015). The objective of this study, therefore, was to develop a systems approach framework for integrated arthropod pest management (IAPM) in the smallholder tomato production system in Kenya.

1.2 Problem statement

According to Schut et al. (2014), overtime, two broad approaches to agricultural innovation have been identified: technology-oriented approach [1950s – 1980s], and systems-oriented approaches (encompassing farming systems [1980s – 1990s], agricultural knowledge and information systems [1990s – 2000s] and agricultural innovation systems [2000s – onwards]).

The transfer of technology approach concerned the development of technologies and knowledge by researchers which were then transferred to farmers and other end-users through extension agents (Schut et al., 2014). Weaknesses of this approach led to the emergence of a more systems-oriented approach to innovation. Specifically, a lack of focus on the context-specific economic, social-cultural and agro-ecological drivers that affect the efficiency of agricultural innovations at a farm (or collection of farms) level led to the emergence of the farming system approach. Later on, there was a progressive shift to bottom-up approaches exemplified by agricultural knowledge and information systems (AKIS). AKIS aims to promote shared learning among value chain actors as a means for sustainable agricultural development. Finally, in agricultural innovation systems (AIS) approach there is a particular focus for the political and institutional dimensions of change processes (Schut et al., 2014).

Within the context of AIS approach, innovation is considered a product of both technological (e.g. agronomic practices, fertilizer, cultivars) and non-technological (e.g. institutional settings and social practices) changes (Schut et al., 2015a). These changes are influenced by interactions among actors within and without the agricultural sector. Furthermore, these changes occur at different levels (e.g. region, farm, field) (Schut et al., 2015a)

Systems approaches are increasingly becoming popular as a pathway to identifying and resolving complicated problems with volatile context that cut-across varied fields and levels of integration, and involve a diversity of stakeholders (Schut et al., 2014, Rodenburg et al., 2015, Schut et al., 2015a, Schut et al., 2015b). The use of systems approaches has been used to elevate the impact and relevance of science in fields such crop science and applied ecology (Rodenburg et al., 2015). It has further been argued that the systems approach is also ideal for the management of research efforts that have an applied objective, including crop protection (Rodenburg et al., 2015, Schut et al., 2015b).

Despite the aforementioned benefits, genuine systems-oriented approaches to crop protection remain largely unexplored (Rodenburg et al., 2015, Schut et al., 2015b). This is because crop protection problems, and their possible solutions, have previously been studied following farmer-participatory approaches and rarely used to inform IPM approaches (De Groote et al., 2010, Rodenburg et al., 2015).

1.3 Justification

The Plantwise programme – an innovative approach to support delivery of agricultural extension service - is used to study arthropod pests' problems in smallholder tomato production systems in Kenya. The programme, working closely with national agricultural advisory services, supports the establishment of networks of community-based plant clinics where farmers can find practical plant health advice.

Plant clinics enhance visibility of rural advisory services to farmers and increase contact between farmers and advisors. Operating as a demand-driven extension tool, plant health clinics run one day weekly or fortnightly in locations readily accessible to smallholder farmers. The farmer brings to the plant clinic a sample of the affected crop, discusses the problem with an experienced agricultural extension officer (also referred to as a "plant doctor") and receives a diagnosis of the plant health problem affecting his or her crop. In addition, the farmer receives a written and verbal recommendation for managing the problem. The farmers visiting plant clinics are small-scale farmers who produce individually or collectively. Production is both for subsistence and income.

Arthropod pests in tomato can be considered a complex crop protection problem (Oduor, 2016, Diatte et al., 2018, Walgenbach, 2018). The problem is influenced by numerous interactions across various integration levels (e.g. crop, farm, soil, climate), affects various stakeholders and is encountered in varied farming systems including subsistence (Hill, 1983, Nault and Speese Iii, 2002, Gornall et al., 2010, Walgenbach, 2018, Olson et al., 2018). There are several arthropod pests in the tropics that are directly associated with tomato damage and yield losses while others are vectors of diseases (Umeh et al., 2002, Olabiyi, 2008, Boubou et al., 2011, Jones et al., 2014).

Relating to their mode of feeding, two main types of crop damage can be associated with arthropod pests. The first is damage attributable to sucking of the plant sap from general tissues of fruits, roots or foliage or from the phloem (or xylem) system. The second is damage due to biting and chewing of plant material (Royalty and Perring, 1989, Imam et al., 2010). Amongst arthropod pests, those that are of economic importance have been identified as spider mites, whiteflies, leafminers, African bollworm, thrips, and aphids (Oduor, 2016).

In relation to pests and developing countries, studies have shown that there are large time gaps between the first sighting, identification, and the eventual development and distribution of suitable pest management strategies (Rodenburg et al., 2015, Cameron et al., 2016). This phenomenon is indicative of a system that is functioning sub-optimally (Rodenburg et al., 2015). In response to this, the Plantwise programme is designed to address plant health problems at various levels (crop, community and country), improve rural livelihoods and increase food security by minimising crop losses. Through partnerships with critical actors, the programme strengthens in-country plant health systems, making possible for countries to avail to farmers information they need to lessen their losses and to feed more (Romney et al., 2013).

The arthropod pest problem in tomato was investigated at three levels: plant/crop, farm and farm household. The primary aim of this approach was to address knowledge gaps in the fields of ecology, socio-economics and management of arthropod pests in tomato cropping systems in Kenya. Specific questions the study targeted were: (1) What are the characteristics and production constraints of smallholder tomato production in Kenya? (2) What is the influence of abiotic factors (agro-ecological zonation) on the distribution patterns of arthropod pests of tomato? (3) What are farmers and extension agents' current practices for management of arthropod pests of tomato? (4) Can adoption of binomial sequential sampling plan contribute to optimization of sampling intensity required for arthropod pest control decisions – case study of a development of a sampling plan for *Tetranychus evansi* on tomato?

Regarding research question 4, as part of developing an IPM strategy, it is critical to be able to approximate, through sampling, arthropod pests' population densities in a practically feasible and reliable manner (Severtson et al., 2016). It has been noted that the lack of user-friendly, cost-effective sampling plans for arthropod pests, particularly among food crops, is a vital constraint to the adoption of IPM (Carvalho, 2016, Severtson et al., 2016, Lima et al., 2017, de Macêdo et al., 2019)

The choice of spider mite for research question four was informed by the fact that, from the time the pest was first reported in Kenya in 2001, it has continued to hinder tomato cultivation in the country (Saunyama and Knapp, 2003, Wekesa et al., 2010, Murungi et al., 2014). Also, for spider mites, both research and commercial operations have long continued to rely on conventional monitoring procedures (e.g. numerical sampling). These procedures are slow, inaccurate and time-consuming. Because of these challenges, there is a push to replace the prohibitively complicated and time-consuming numerical sampling with techniques that are less complex and offer realistically accurate estimations within a reasonable timeframe (Alatawi et al. 2005). Binomial (presence-absence) sampling conforms to this criterion and is well suited for spider mite since rather than counting individual mites; infested leaves are the ones counted (Alatawi et al. 2005). The use of binomial sampling has successfully been employed in some pest control systems for an array of pests (Naranjo et al., 1996, Butler and Trumble, 2012, Cocco et al., 2015).

1.4 Objective

The main objective of the study was to develop a systems approach framework for integrated arthropod pest management (IAPM) in the smallholder tomato production system in Kenya. The specific objectives were:

(1) To determine characteristics and production constraints of smallholder tomato production in Kenya
(2) To determine the influence of abiotic factors (agro-ecological zonation) on the distribution patterns of arthropod pests of tomato
(3) To evaluate farmers and extension agents’ current practices for management of arthropod pests of tomato in Kenya
(4) To develop an appropriate sampling plan for a major arthropod pest of tomato in Kenya

1.5 Hypotheses

(1) Understanding characteristics and production constraints of smallholder farming system is crucial in the design of a successful IAPM programme
(2) Abiotic factors influence distribution patterns of arthropod pests.
(3) Knowing pest management practices extension agents and farmers are recommending and using, respectively, ensures IAPM programmes are able identify actions required for sustainable pest management
(4) Adoption of a binomial sequential sampling plan can contribute to optimization of sampling intensity required for arthropod pest control decisions

CHAPTER 2
LITERATURE REVIEW

2.1 General information about tomato

2.1.1 General description

The cultivated tomato is associated with the nightshade family Solanacea, a medium-sized angiosperm family, which has other crops of economic importance, including potato, tobacco, pepper and eggplant (Wu and Tanksley, 2010, Oduor, 2016). The crop is an annual plant. Its tap root system, which can grow to a depth of 50cm or more, produces dense adventitious and lateral roots. The stem, ranging from erect and prostrate, can grow to a height of 4m. Leaves are spirally arranged and measuring 15-50cm x 10-30cm (Naika et al., 2005). Leaflets are variously shaped – some are ovate in shape while others are oblong and covered with glandular hairs. Tomato flowers are bisexual and grow opposite or between leaves. Immature tomato fruits are green in colour and hairy while ripe fruits range from red, orange and yellow. Finally, tomato seeds are pear or kidney shaped and hairy (Naika et al., 2005).

Tomato cultivars can be categorised depending on growth habit (determinate, indeterminate, and semi-determinate); utilisation (for processing of fresh market); fruit shape (pear-shaped, heart-shaped, plum-shaped, flat or elongated); fruit size (small round, medium-large round, ribbed and beefsteak) and colour of ripe fruit (yellow, orange, pink or red) (Naika et al., 2005, Oduor, 2016).

2.1.2 Origin and distribution of tomato

Relatives of the cultivated tomato occurring in the wild are indigenous to western South America alongside the coastline and high Andes from northern Chile, through Peru, to central Ecuador, and in the Galapagos Islands (Peralta and Spooner, 2007). The most plausible forebear of planted tomatoes is the wild cherry tomato (*Solanum lycopersicum* var. cerasiforme), that is more widespread and possibly in the recent past distributed into South American countries, including Bolivia, Colombia, and Mexico (Peralta and Spooner, 2007).

Two competing hypotheses have been forwarded regarding the country of origin of the cultivated tomato, when it arrived in Europe for the first time and who took it there (Jenkins, 1948, Peralta and Spooner, 2007). Most experts are agreed that cultivated tomato was transported from Peru to Europe by Spanish conquistadors immediately following the conquest in 1535. On the other hand, the prospects of a Mexican origin have also been raised, though the substantive proof mentioned in favour of this hypothesis is minimal (Jenkins, 1948, Naika et al., 2005).

In Europe, tomatoes were initially cultivated as curiosity or ornamental plants and were considered by many to be inedible or poisonous on account of resembling poisonous belladonna or mandrake. The crop was first accepted as a vegetable crop in the late sixteenth century in southern Europe (Peralta and Spooner, 2007). In Africa, tomato was most likely introduced by Europeans towards the end of the twentieth century (Biney, 2001)

2.1.3 Classification and taxonomy of tomato

For the longest time tomato was known as *Lycopersicum esculentum*. However, recent research has led to the crop being renamed *Solanum lycopersicum* – reverting to its original name (OECD, 2016). The tomato clade consists of 12 wild relatives and the cultivated tomato (*Solanum lycopersicum*) which is derived from 2 wild ancestor species, *Solanum cerasiforme* and *Solanum pimpinellifolium*. The wild relatives of cultivated tomato display a high degree of genetic and phenotypic divergence, including a great variation in reproductive biology and mating systems (OECD, 2016).

2.1.4 Uses and nutritional importance of tomato

Tomato is a valuable source of nutrients, contributing immensely to well-balanced and healthy diets (Appendix 1) (Naika et al., 2005, USDA, 2018). The crop is cooked in dishes, soup or sauces or consumed fresh in salads. Furthermore, it can be processed into ketchup, purées and juices (Naika et al., 2005).

2.1.5 Tomato value chain

The tomato value chain, comprise of the following divisions: provision of inputs, production, packing and cold storage, processed fruit and vegetables, and distribution and marketing (Staritz and Reis, 2013).

Among the crucial inputs required for production of cultivated tomato are seeds, fertilizers, farm equipment and agrochemicals (Fernandez-Stark et al., 2011). Production, on the other hand, can be divided between production for processed fruit and vegetables and production for fresh consumption.

Along the value chain, the first step in the packing stage is grading. Other processes that could occur in this stage include washing, chopping, mixing, packing and labelling. The produce is then placed in cold storage units as it awaits transportation (Fernandez-Stark et al., 2011). Processed fruit include dried, frozen and preserved produce besides juices and pulps (Naika et al., 2005). Finally, the produce is distributed using an array of channels which include small-scale retailers, wholesalers, supermarkets, and food services (Naika et al., 2005, Fernandez-Stark et al., 2011)

2.2 Constraints to smallholder tomato production in Kenya

Smallholder agriculture is important when it comes to food security, primarily for two reasons: as a source of income and food for a majority of people living in poverty (Arias et al., 2013). Small-scale agriculture is marked by modest production volumes of variable quality, faces an array of challenges which include: pests and diseases; non-competitive markets; low levels of investment; inadequate infrastructure – credit, production and market information; limited access to inputs that would enhance productivity (such as improved seed and fertilizers); immense levels of production uncertainty and risk; and lack of access to improved technologies and agricultural practices etc.

2.2.1 Pests of tomato

According to Oerke (2006), pests curtail crop productivity through different mechanisms, which based on their impacts can be categorised into: tissue consumers (necrotrophic pathogens, chewing animals), assimilate sappers (sucking arthropods, nematodes, pathogens), photosynthetic rate reducers (viruses, bacteria, fungi), stand reducers (pathogens, damping-off), light stealers (some pathogens, weeds), and leaf senescence accelerators (pathogens).

Invertebrate pests

There are many biotic and abiotic factors that affect tomato production (Biney, 2001, Naika et al., 2005, Oduor, 2016). Amongst invertebrate pests, much as there are several species that are associated with tomato, those that are of economic importance have been identified as spider mites, whiteflies, leafminers, African bollworm, thrips, aphids and nematodes (Oduor, 2016).

Spider mites (*Tetranychus* spp.) are less than 1mm in size, lay their eggs on the underside of tomato leaves, and appear in varied colours ranging from red, green, orange and yellow – the colours being the result of different haemolymph pigments (Navajas et al., 1998, Naika et al., 2005, Oduor, 2016). Owing to their small sizes, *Tetranychus* spp. damage in most instances remain unnoticed until symptoms of damage caused by them become noticeable (Migeon et al., 2009). The adult and larval stages of *Tetranychus* spp suck sap from the leaves, leading to the leaves becoming yellow and dry. Additionally, the mites form an airy web of thin threads that resemble those formed by spiders (Naika et al., 2005). Hot and dry weather favours outbreak of *Tetranychus* spp. (Hollingsworth and Berry, 1982).

Whiteflies (*Bemisia tabaci* Gennadius) cause damage to crops by transmitting many plant viruses, secreting honey dew and weakening plants (Skaljac et al., 2010). Adult whiteflies are 1-2mm long; possess two pairs of white wings and their bodies coated with wax (Naika et al., 2005, Liburd et al., 2008). Adult female reproduces parthogenetically (reproduction in the absence of fertilization) and can produce as many as 300 eggs which are laid on the underside of leaves. The length of the insect’s lifecycle is dependent on temperature (Liburd et al., 2008).

The damage caused by leafminers (*Liriomyza* spp. Burgess) on tomato can be categorised into two (indirect and direct) (Trumble, 1985). Direct damage, mostly the result of larval feeding, is the most severe. Here, the mining activity of the larval stage lower the capacity of the plant to photosynthesise and in heavy infestations, the larvae cause desiccation and untimely fall of leaves (Trumble, 1985). On the other hand, feeding punctures, the result of activity by adult females, can be breached by bacteria and fungi. Also, in certain instances leafminers have been shown to transmit viruses (Trumble, 1985).

African bollworm (*Helicoverpa armigera* Hubner), an indigenous species, is a major constraint to tomato production in Africa (Biney, 2001, Cherry et al., 2003, Oduor, 2016). The pest is polyphagous, has a high fecundity and brief generation time. In addition, the pest has a high mobility, a propensity for developing resistance to insecticides, and the larval stage prefers harvestable fruiting parts of host plants (Cherry et al., 2003). The larvae of *Helicoverpa armigera* bore into the fruit where they feed on the fruit’s inner parts. The action of feeding by the bollworm leads to tomato fruit rot on account of secondary infections by fungal and bacterial pathogens which enter the fruit via the feeding holes (Mueke, 2014).

Thrips (*Frankliniella occidentalis* Pergade) larvae and adults puncture tomato leaves and suck leaf sap, resulting in the attacked leaves having on their surface silvery spots. Also, adult thrips leave its excreta, appearing as small blacks dots, on the leaf surface (Naika et al., 2005, Mueke, 2014). In instances of heavy infestation, the pest causes: distortion of young shoots, delay in leaf development and premature wilting. Abortion often occurs whenever the pest attacks flowers (Mueke, 2014). Finally, the pest vectors tomato chlorotic spot virus and tomato spotted wilt virus (Naika et al., 2005, Mueke, 2014).

Aphids (*Aphis gossypii* Glover) mostly attack the terminal shoots and feed on the underside of leaves. In addition, they facilitate the development of sooty moulds on leaves and on the fruit (Biney, 2001). Indirectly, aphids transmit various viruses (Naika et al., 2005).

Root-knot-nematodes (*Meloidogyne* spp) are of primary importance when it comes to cultivation of tomatoes. The pests produce galls and root swellings on plant roots. As a result of the infestation, affected plants remain small and predisposed to soil-borne pathogens (bacteria and fungi) (Naika et al., 2005)

Diseases

Like invertebrate pests, diseases equally pose a threat to tomato production (Biney, 2001, Naika et al., 2005, Oduor, 2016). It has been stated that there are over 200 known diseases, comprising fungi, virus and bacteria, that attack tomatoes. Virus infection often results in dwarfed growth among plants which in turn impacts yields. On the other hand, bacteria and fungi cause leaf, stem, root and fruit diseases (Naika et al., 2005, Oduor, 2016). Some of the major diseases of tomato in Kenya include *Fusarium* wilt, early and late blight, septorial leaf spot, bacterial spot, powdery mildew tobacco mosaic virus and yellow leaf curl virus (Oduor, 2016).

2.2.2 Abiotic constraints

Nutrient deficiency, salinity, drought, heat and cold are abiotic stressors that adversely affect tomato growth and development, resulting in widespread losses in crop production (Naika et al., 2005, Oduor, 2016). Sensitivity to water shortage differs amongst various crops and, of horticultural crops, tomato is renowned to be vulnerable to water stress particularly at flowering and fruit formation stages. Consequently, making provisions for appropriate water supply to tomato plant is important for the crop’s growth (Oduor, 2016).

2.3 Management of pests

Crop losses due to invertebrate pests, fungi, bacteria, virus and other harmful organisms can be enormous (Oerke, 2006, Hashemi et al., 2009). According to Oerke (2006), crop losses can be qualitative and/or quantitative. Qualitative losses as a result of pests can manifest themselves in the form of decreased content of beneficial ingredients, decreased quality for the market e.g. as a result of aesthetic characteristics (such as pigmentation), diminished storage characteristics etc. On the other hand, a quantitative loss is the product of diminished productivity which leads to lowered yield per unit area.

Crop productivity has been under threat from pests since the onset of agriculture, and farmers have been exploring mechanisms of safeguarding their produce from these organisms. Initially, control of animal pests largely relied on hand-picking of larval stages of insects. Diseases resulting from microscopic organisms were rarely considered as pest-related and management practices were reduced to the usage of land races adapted for growing conditions occurring in local contexts (Oerke, 2006). The use of chemicals for control of diseases began with the use of first generation of fungicides (organic mercury, sulphur and copper) over a century ago. Second generation of fungicides consisted of organic chemicals operating as surface protectants. Finally, third generation of fungicides have ability to pierce the plant tissue and have ability to manage established infections in a way that is curative – a requirement for threshold-oriented application of fungicides (Oerke, 2006). In the same vein, there is also a longstanding tradition of use of insecticides and acaricides for the management of arthropod pests. A limitation, however, associated with high frequency application of insecticides and acaricides is the emergence of insects and mites, respectively that are resistant to the concerned pesticides’ active ingredient (Oerke, 2006).

The use of *Bacillus thuringiensis* insecticide for the management of lepidopterous pests was first deployed in 1972. To date, biological control of plant pathogens and arthropod pests through use of antagonistic organisms is mostly confined to greenhouses, which only account for a minimal percentage of the entire production area. Natural enemies comprise arthropod pathogens and predators and insect parasites (Oerke, 2006).

Further developments in crop protection concerned the development of Integrated Crop

Management (ICM) as a mechanism for managing crop pests. ICM by definition, according to Oerke (2006), is the inexpensive production of high calibre crop through prioritizing ecological safe means of cultivating the crop, and reducing the unpleasant side effects and use of products employed for crop protection. ICM includes Integrated Pest Management (IPM) which focuses on protection of crops (Kumar and Singh, 2014). Both IPM and ICM strategies fuse an array of complementary mechanisms in order to minimise pest populations to just below economic injury level. At the same time, strategies of both approaches reduce impacts on environmental conditions and on other elements of the agro-ecosystem (Kumar and Singh, 2014). In ICM, synthetic pesticides are used discriminately in a manner that supplement other management practices (biological, physical, and cultural methods), and as a consequence reduce the chances of pests developing resistance against synthetic pesticides (Kumar and Singh, 2014).

2.4 Plantwise programme

Plantwise is a global programme that is led by Centre for Agriculture and Bioscience International (CABI). The programme supports farmers to mitigate their losses on account of crop pests. By collaborating with government agricultural advisory services, the programme promotes the establishing of networks of community-based plant clinics. Here, farmers are able to benefit from plant health advice.

The community-based plant clinics operate as a demand-driven extension tool (Figure 1). They work one day in a week or after every two weeks in locations that are convenient to smallholders. At the plant clinic, a farmer brings a sample of the affected crop. The farmer then confers with a knowledgeable agricultural extension agent regarding the problem. Upon making a diagnosis, the experienced agricultural extension agent recommends, verbally and in writing, an appropriate management strategy for the plant health problem.

Nderi plant clinic , Kiambu county

Subuukia plant clinic, Nakuru county

Kithumu plant clinic, Embu county

Uranga Usonga plant clinic, Siaya county

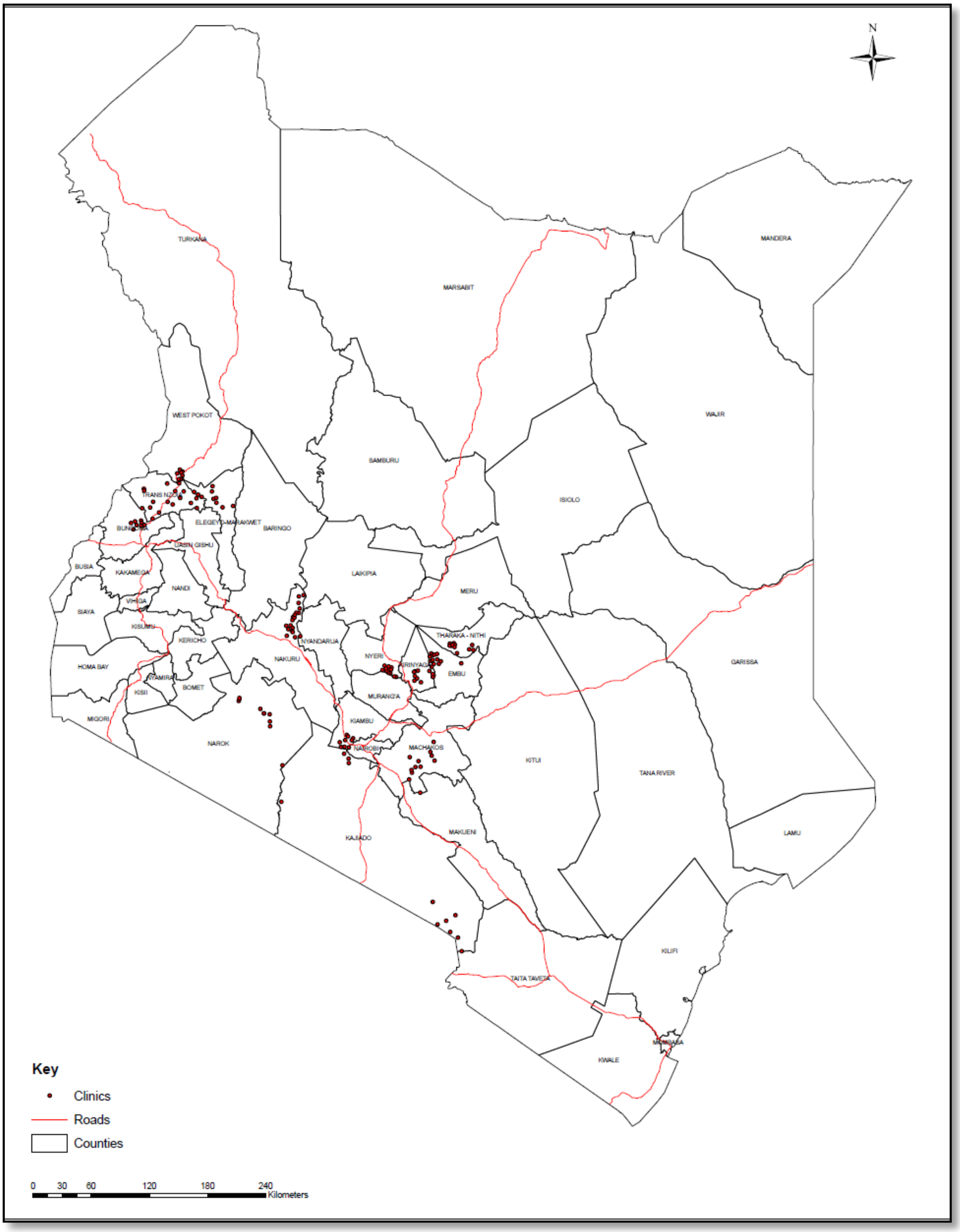
Kimilili plant clinic, Bungoma county

Cherengany pant clinic, Trans Nzoia county

Figure 1: Plant clinic sessions in various locations in Kenya

For their training, plant doctors undergo four areas of training and capacity building (offered by Plantwise) to enable them run plant clinics, collect plant health data, develop extension materials and monitor plant clinic operations. These are: module 1: focuses on how to do a field diagnosis through observation of diseased/infested plant's symptoms and listening to farmers; module 2: focuses on how to give locally relevant plant health management advice to farmers, using available and affordable inputs and how to recognize when to seek expert help; module 3: focuses on how to translate plant health management advice and knowledge into simple factsheets that can be understood by farmers; and module 4: Focuses on establishing quality assurance to improve clinic services (including data management). Globally, Plantwise is implemented in 34 countries (12 in Africa: Kenya, Uganda, Tanzania, Rwanda, Ethiopia, Democratic Republic of Congo, Ghana, Burkina Faso, Sierra Leone, Malawi, Zambia and Mozambique).

In Kenya, Plantwise was launched in May 2012 after a successful 2-year piloting phase. The Ministry of Agriculture, Livestock and Fisheries (MoALF) through the Extension and Training directorate is leading Plantwise implementation in close partnership with relevant players in the plant health system. Among these players include regulatory agencies (Kenya Plant Health Inspectorate Services (KEPHIS) and Pest Control Products Board (PCPB)), agricultural research and learning institutions (Kenya Agricultural and Livestock Research Organization (KALRO), University of Nairobi (UON)), agro-input providers (Agrochemicals Association of Kenya (AAK), Non-Governmental Organizations (NGOs), Community Based Organizations (CBOs) and Private sector. During the piloting phase (2010 – 2011), 40 plant doctors were trained to run an initial 25 plant clinics. In the course of this period, farmers and extension staff reported that clinics enabled them better address plant health issues and thus have a crucial role to play in increasing food security. Following this positive feedback, MoALF increased the number of plant clinics across the country. By the end of 2018 there were a total of 600 plant doctors manning a total of 300 plant clinics (Figure 2 and Appendix 2).



Source: Plantwise Kenya (CABI)

Figure 2: Location of plant clinics in Kenya

CHAPTER 3

CHARACTERISTICS AND PRODUCTION CONSTRAINTS OF SMALLHOLDER TOMATO PRODUCTION IN KENYA

3.1 Introduction

Agriculture remains central to Kenya’s economy accounting for 32.6 per cent of the country’s Gross Domestic Product (GDP), which is valued at KES 7.2 trillion (Mwega and Ndung’u, 2004, Diao et al., 2010, KNBS, 2017). In addition, it is estimated that 75 percent of the population, either directly or indirectly, depend on the sector (RSA, 2015). In particular, the horticulture sub-sector of agriculture has grown to be a vital source of income for smallholder farmers, government revenue, and foreign exchange earnings. Furthermore, the sub-sector contributes immensely to food security, as well as being a crucial source of raw materials for the manufacturing sector (KENDAT, 2015). The main horticultural crops produced include vegetables, fruits, herbs, root crops (Irish and sweet potatoes), spices and cut flowers (Ongeri, 2014).

Tomato, a popular and extensively cultivated vegetable, is among the promising commodities in horticultural production in Kenya (Karuku et al., 2017, Wafula et al., 2018). The crop is eaten by nearly all of the households as a source of vitamins A and C and lycopene (Asante et al., 2013). Notwithstanding, tomato yields over the years in Kenya have remained low due to a myriad of impediments. For the management of biotic constraints, overreliance and indiscriminate use of chemical products among smallholder farmers has been reported (Asante et al., 2013). This dependency on pesticides potentially poses a health hazard to growers and consumers besides associated environmental effects (Asante et al., 2013). Another constraint leading to low tomato yields is the failure of smallholder farmers to take advantage of available technologies such as use of improved seeds (Geoffrey et al., 2014). The use of improved seeds could potentially aid farmers attain the utmost achievable yield level (Asante et al., 2013). In appreciation of this, efforts have gone towards improving tomato production by means of developing improved varieties that are high yielding, resistant to pests amongst other sought qualities.

A missing component in studies on tomato production in Africa is characterisation of smallholder tomato producing households and determination of their technical efficiency

(Asante et al., 2013). Besides describing tomato farmers, it is necessary to investigate the causes of technical efficiency and productivity among them. Knowing this will highlight the extent to which inputs such as improved varieties and other factors account for disparities in yield. This paper thus seeks to characterise tomato producing households in Kenya by (1) describing demographic characteristics of sampled farmers, (2) investigating production practices and (3) identifying challenges and opportunities for increased productivity on smallholder production.

3.2 Materials and methods

3.2.1 Study overview

This study examined data collected from plant clinics in 121 locations over a four-year period (June 2013 to May 2017). The 121 locations where the data were collected were distributed in 14 counties of Kenya: Nyeri, Kirinyaga, Embu, Tharaka Nithi, Machakos, Kiambu, Nakuru, Trans Nzoia, Bungoma, Elgeyo Marakwet, Kajiado, Siaya, Narok and West Pokot. In relation to their prominence, the 14 counties account for only 11 percent of total land in Kenya, but for 23 percent of arable land. In addition, the 14 counties are the major tomato growing areas in Kenya (Table 2).

Table 2. Production of tomato in Kenyan counties from 2012 - 2014

County	2012			2013			2014		
	Area (Ha)	Volume (MT)	Value (Million KES)	Area (Ha)	Volume (MT)	Value (Million KES)	Area (Ha)	Volume (MT)	Value (Million KES)
Kirinyaga	1,903	59,464	1,159	1,796	30,774	750	1,648	48,560	1,156
Kajiado	1,603	35,937	921	1,668	50,884	962	1,680	47,368	1,624
Bungoma	1,344	39,232	1,221	1,474	41,568	1,228	1,700	50,399	1,611
Kisumu	822	12,219	347	1,537	14,307	444	1,477	16,720	328
Kisii	876	15,590	331	951	16,985	364	937	16,664	351
Kiambu	964	18,029	811	691	9,169	419	964	18,029	812
Trans Nzoia	480	9,270	129	623	17,395	302	628	14,848	416
Machakos	547	10,335	222	724	11,548	323	447	6,189	356
Nakuru	509	6,745	602	495	8,668	516	633	17,511	347
Makueni	431	17,582	651	486	22,560	991	558	21,096	857
Others	9,706	139,702	3,992	10,540	160,010	5,353	13,402	142,820	3,945
Total	19,185	364,105	10,386	20,985	383,868	11,652	24,074	400,204	11,803

Source: Horticultural Crops Directorate (HCD) validated report 2014; Mi- million, MT- metric tons, Ha- hectare

During the period under review a total 37,051 smallholder farmers visited plant clinics in 121 locations. Of these, 4,907 were tomato farmers. To avoid bias, records of repeat visits by farmers were omitted from the data that was considered in this study, meaning ‘one farmer one record’.

Data management system

The process of collecting data and management of the same was divided into stages. Table 3 displays the stages and actors involved.

Table 3. Stages in the data management system process and actors involved

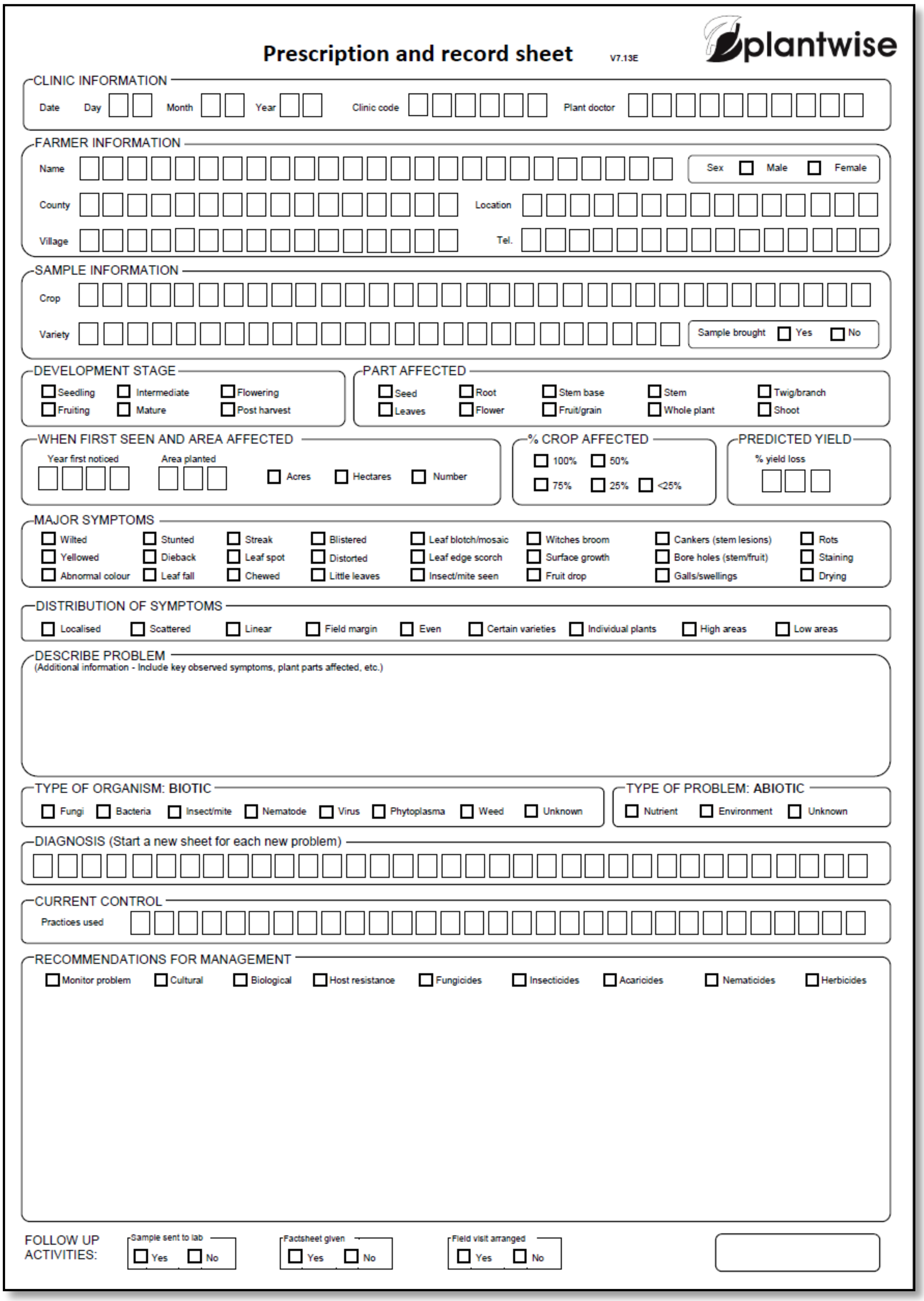
Data management system category	Data management system step	Actors involved
Data collection	1. Recording	Plant doctors
	2. Transfer	Plant doctors, via data entry hubs
	3. Data entry	Data clerks
Data processing	4. Harmonization	Researcher
	5. Validation	Researcher.
Data use	6. Analysis	Researcher

Data collection

At the point of collecting data, ‘plant doctors’ utilised the Plantwise prescription form (Figure 3) to capture information about farmers’ queries. Besides recording information about the farmer and the plant clinic, the ‘plant doctors’ recorded information about the crop, variety, symptoms and diagnosis and pest management practices. Upon completion, the filled prescription forms were collated and transported to the national data hub in Nairobi. Data entry was achieved by means of an Excel-based form resembling the prescription form.

Data processing

Harmonization of data involved cleaning of digitized data (diagnoses and crop names, plant doctor names and location details). At data validation stage, the researcher reviewed all the 4,907 plant clinic records to check the accuracy of the diagnoses. Validating diagnoses was done by checking that: (1) a diagnosis was recorded in the form; (2) it was specific to at least sub-group level (e.g. mites, mealybugs, thrips, etc.); (3) it was plausible (i.e. known to affect the host crop and has previously been reported in the country); (4) key symptoms of the diagnosed pest were recorded and; (5) it was definitive (symptoms were not easily confused with other causes); and (6) the picture of the sample accompanying the record confirmed the diagnosis.



plantwise

Prescription and record sheet V7.13E

CLINIC INFORMATION

Date Day ☐☐ Month ☐☐ Year ☐☐ Clinic code ☐☐☐☐☐☐ Plant doctor ☐☐☐☐☐☐☐☐☐☐

FARMER INFORMATION

Name ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ Sex ☐ Male ☐ Female

County ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ Location ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

Village ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ Tel. ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

SAMPLE INFORMATION

Crop ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

Variety ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐ Sample brought ☐ Yes ☐ No

DEVELOPMENT STAGE

☐ Seedling ☐ Intermediate ☐ Flowering
☐ Fruiting ☐ Mature ☐ Post harvest

PART AFFECTED

☐ Seed ☐ Root ☐ Stem base ☐ Stem ☐ Twig/branch
☐ Leaves ☐ Flower ☐ Fruit/grain ☐ Whole plant ☐ Shoot

WHEN FIRST SEEN AND AREA AFFECTED

Year first noticed ☐☐☐☐ Area planted ☐☐☐ ☐ Acres ☐ Hectares ☐ Number

% CROP AFFECTED

☐ 100% ☐ 50%
☐ 75% ☐ 25% ☐ <25%

PREDICTED YIELD

% yield loss ☐☐☐

MAJOR SYMPTOMS

☐ Wilted ☐ Stunted ☐ Streak ☐ Blistered ☐ Leaf blotch/mosaic ☐ Witches broom ☐ Cankers (stem lesions) ☐ Rots
☐ Yellowed ☐ Dieback ☐ Leaf spot ☐ Distorted ☐ Leaf edge scorch ☐ Surface growth ☐ Bore holes (stem/fruit) ☐ Staining
☐ Abnormal colour ☐ Leaf fall ☐ Chewed ☐ Little leaves ☐ Insect/mite seen ☐ Fruit drop ☐ Galls/swellings ☐ Drying

DISTRIBUTION OF SYMPTOMS

☐ Localised ☐ Scattered ☐ Linear ☐ Field margin ☐ Even ☐ Certain varieties ☐ Individual plants ☐ High areas ☐ Low areas

DESCRIBE PROBLEM
(Additional information - Include key observed symptoms, plant parts affected, etc.)

TYPE OF ORGANISM: **BIOTIC**

☐ Fungi ☐ Bacteria ☐ Insect/mite ☐ Nematode ☐ Virus ☐ Phytoplasma ☐ Weed ☐ Unknown

TYPE OF PROBLEM: **ABIOTIC**

☐ Nutrient ☐ Environment ☐ Unknown

DIAGNOSIS (Start a new sheet for each new problem)

☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

CURRENT CONTROL

Practices used ☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐

RECOMMENDATIONS FOR MANAGEMENT

☐ Monitor problem ☐ Cultural ☐ Biological ☐ Host resistance ☐ Fungicides ☐ Insecticides ☐ Acaricides ☐ Nematicides ☐ Herbicides

FOLLOW UP ACTIVITIES:

Sample sent to lab ☐ Yes ☐ No
Factsheet given ☐ Yes ☐ No
Field visit arranged ☐ Yes ☐ No

Figure 3: Plantwise prescription form

Data analysis

Analysis of data was executed using a statistical programme, SPSS, version 16 (SPSS, Released 2007). The analyses included assessing trends over time, and reviewing recommendations from prescription forms. To gauge the comparative frequency of variables, cross tabulation was employed and assessed for significance using the Pearson Chi-square test. Associations between nominal dependent variables (seed variety, pest type and pest management intervention) and many independent variables (seed variety – cost of seeds, growth habit of tomato plant, and tomato use; pest type – time, location and tomato variety; and pest management intervention – time, location and causative agent) were examined using multinomial logistic regression, and Goodness-of-fit test used to examine how well the model fits the data. ANOVA and Student's t-test were deployed to compare group means. Significance was defined as a p value ≤ 0.05.

3.3 Results

3.3.1 Farm demographics

Farm demographic data is summarised in Table 4. The study indicated male dominance in tomato production in Kenya. A majority of the smallholder tomato farmers were male (69%). Of the smallholders who provided their age, 23% were between the ages 20 – 35 years. On the other hand, 73% of the farmers were between 36 – 60 years while the rest (4%) were above 60 years. The area under tomato production ranged from 0.006 acres – 2 acres with a majority of the farmers planting tomatoes in an eighth of an acre or less (Figure 4). There were significant ($p \leq .05$) differences between areas under tomato cultivation by male farmers (0.32 acres) and those under cultivation by female farmers (0.24 acres), t (4788) = 7.220, $p<0.001$.

Table 4: Demographic characteristics of respondents

(a) Categorical variables

	Number of farms (*n* = 4,907)	Percentage (excluding missing values)
Farmer's gender		
Male	3,297	68.8
Female	1,493	31.2
Missing value	117	-
Farmer's age		
Youth	303	22.9
Adult	971	73.3
Senior	50	3.8
Missing value	3,583	-
Farm location		
Rural	3,571	72.8
Peri-urban	1,336	27.2

(b) Continuous variable

	Mean	Median	Range
Farm size (acres)	0.292	0.131	0.006 – 2.0

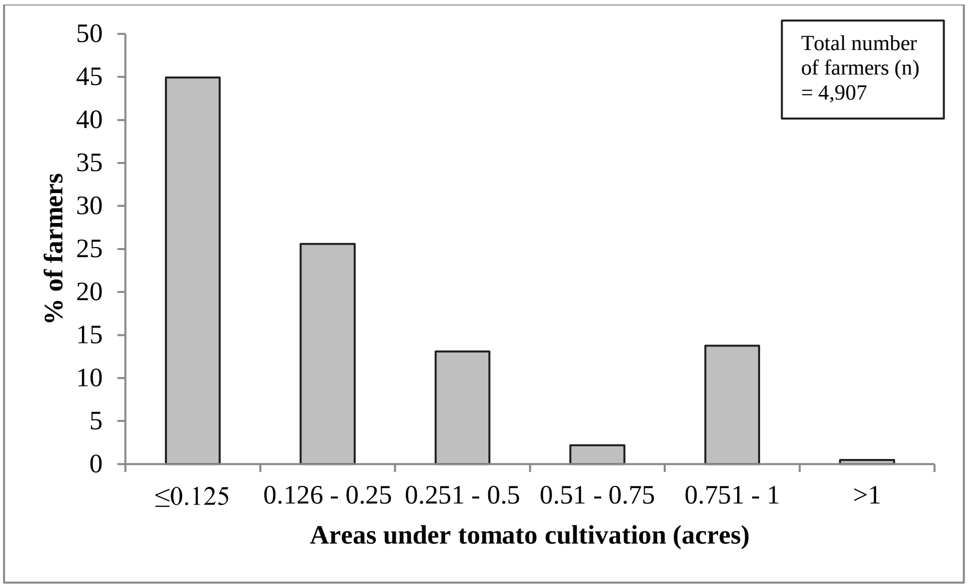


Figure 4. Area under tomato cultivation

Also, over time, there was a statistically significant (p≤.05) difference in the area under tomato cultivation as determined by one-way ANOVA (F (3, 4903) = 13.542, p<0.001) (Table 5). Further analysis indicated that the areas under tomato cultivation significantly declined in the third and fourth years of the study (Table 5). Areas under tomato cultivation, however, was not significantly affected by the location of the farmer (rural/peri-urban) (t (4905) = 0.983, p = 0.326) as well as the age of the farmer (youth/adult/senior) (F (2, 1321) = 1.625, p=0.197) (Table 5).

3.3.2 Access to high quality seeds

The three main tomato varieties grown in Kenya and their corresponding percentage of farmers involved in their cultivation are Rio grande (32%), Cal J (16%) and Kilele F1 (11%) (Figure 5). It is more likely that the choice of tomato variety cultivated was influenced by the cost of the seeds, the growth habit of the tomato plant (determinate vs indeterminate), and tomato uses (processing vs fresh market types) (Table 6). Most of the smallholders (64%) opted for cheaper tomato varieties (cost less than KES 1,000). Over time, however, the numbers progressively declined. This culminated in nearly half of the farmers, by fourth year of the study, going for varieties that were medium priced (cost KES 1,000 – 10,000). Conversely, the number of smallholders (13%) opting for expensive varieties (cost greater than KES 10,000) remained the same throughout the duration of the study. There was an overwhelming (84%) preference for determinate varieties compared to indeterminate varieties (16%), and this phenomenon was reflected throughout the duration of the study. A majority of the smallholders (63%) selected varieties ideal for processing while the remaining 37% cultivated fresh market tomatoes.

Table 5. Descriptive statistics for farm size

	n	Average farm size (acre)	SD	Student's t-test
Farmer gender				
Male	3297	0.32	0.35	t(4788) = 7.220, p<0.001
Female	1493	0.24	0.30	
Farm location				
Rural	3571	0.29	0.34	t(4905) = 0.983, *p* = 0.326
Peri-urban	1336	0.30	0.35	
Farmer age				
Youth	303	0.24	0.33	(*F* (2, 1321) = 1.625, *p*=0.197)
Adult	971	0.26	0.33	
Senior	50	0.17	0.26	
Study period				
Year 1	766	0.30ab	0.32	(*F* (3, 4903) = 13.542, *p*<0.001)
Year 2	1329	0.33a	0.36	
Year 3	1439	0.30ab	0.34	
Year 4	1373	0.25c	0.32	

*Means, within a column, followed by the same letter are not significantly different from each other at p ≤ 0.05 (Fisher's Least Significant Difference Test)

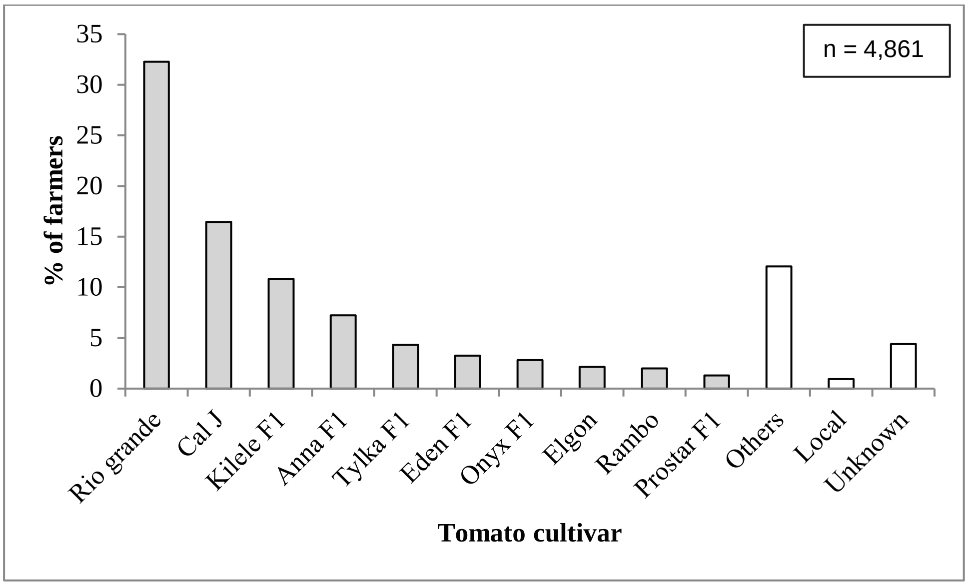


Figure 5. Preferred tomato varieties by smallholder farmers in Kenya

Table 6. Summary of results of Multinomial Logistic Regression for relationship between test variables (farmers' location and gender; cost of seeds; plant growth type; and plant use) and choice of tomato variety

Test variables	Chi-Square	df	*p*
Location	7.632	12	.813
Gender	14.106	12	.294
Cost of Seeds	574.514	12	**<0.01**
Growth habit	70.734	12	**<0.01**
Crop uses	736.134	12	**<0.01**
Goodness-of-Fit (analysis)	219.985	372	**1.000**

3.3.3 Tomato production constraints and intervention

Constraints

A diverse range of constraints impede tomato production. These include pests and abiotic factors. The major groups of pests and abiotic factors impeding tomato production were insects (34%), fungi (23%), bacteria (13%), nutrient deficiencies (12%), mites (8%), viruses (3%), nematodes (2%), and water moulds (2%). It is highly likely that frequencies of biotic and abiotic constraints were influenced by the time, tomato variety and location (Table 7).

Table 7. Summary of results of Multinomial Logistic Regression for relationship between test variables (study period, farmers' location, tomato variety) and incidences of biotic and abiotic constraints

Test variables	Chi-Square	df	Sig.
Study period	135.441	39	**<.001**
Location	32.908	13	**.002**
Variety	273.956	130	**<.001**
Goodness-of-Fit (analysis)	948.554	1105	**1.000**

Incidences of pest showed considerable inter-year differences, particularly for insects, bacteria, fungi, nematodes and viruses. Over time, incidences of insect pests increased (from 26% [2013] to 36% [2017]) while incidences of bacteria (from 12% [2013] to 11% [2017]), fungi (from 27% [2013] to 22% [2017]), nematodes (from 3% [2013] to 1% [2017]) and viruses (from 5% [2013] to 2% [2017]) decreased. On the other hand, incidences of mites (10%), nutrient deficiencies (12%) and water moulds (2%) marginally varied over time.

Certain tomato varieties were more susceptible to infestation by arthropod pests or disease attack than other varieties (Table 8). For instance, while Elgon variety had the highest incidence of insect pests, it recorded the least incidence of fungal diseases.

Pest damage was variable and site-specific. There were more reported cases of bacteria and insects in peri-urban locations (15% and 36%, respectively) than in rural locations (12% and 34%, respectively) while more cases of mites were recorded in rural locations (9%) than in peri-urban areas (7%).

Table 8. Cross tabulation showing frequencies and percentages (represented in brackets) of various biotic and abiotic constraints among an array of varieties in smallholder tomato production in Kenya

	Bacterium	Fungus	Insect	Mite	Nematode	Nutrient deficiency	Viruses	Water mould	Others
Rio grande	177 (11%)	407 (26%)	523 (33%)	156 (10%)	45 (3%)	136 (9%)	61 (4%)	38 (2%)	16 (1%)
Cal J	106 (13%)	198 (25%)	220 (27%)	86 (11%)	19 (2%)	135 (17%)	19 (2%)	7 (1%)	8 (1%)
Kilele F1	62 (12%)	100 (19%)	213 (40%)	32 (6%)	7 (1%)	63 (12%)	19 (4%)	16 (3%)	11 (2%)
Anna F1	55 (16%)	69 (20%)	135 (38%)	14 (4%)	12 (3%)	48 (14%)	4 (1%)	8 (2%)	7 (2%)
Tylka F1	17 (8%)	42 (20%)	90 (43%)	13 (6%)	2 (1%)	31 (15%)	3 (1%)	1 (0%)	6 (3%)
Eden F1	31 (20%)	26 (17%)	55 (35%)	7 (4%)	2 (1%)	27 (17%)	1 (1%)	3 (2%)	6 (4%)
Onyx F1	17 (12%)	34 (25%)	46 (34%)	13 (9%)	2 (1%)	15 (11%)	4 (3%)	4 (3%)	3 (2%)
Elgon	2 (2%)	17 (16%)	60 (57%)	16 (15%)	4 (4%)	3 (3%)	1 (1%)	2 (2%)	1 (1%)
Rambo	15 (15%)	24 (25%)	31 (32%)	1 (1%)	2 (2%)	14 (14%)	5 (5%)	3 (3%)	2 (2%)
Prostar F1	9 (14%)	15 (23%)	20 (31%)	5 (8%)	1 (2%)	11 (17%)	2 (3%)	0 (0%)	1 (2%)
Others	95 (16%)	138 (24%)	188 (32%)	38 (7%)	6 (1%)	70 (12%)	20 (3%)	13 (2%)	18 (3%)
Local	5 (11%)	9 (20%)	13 (28%)	5 (11%)	3 (7%)	7 (15%)	2 (4%)	1 (2%)	1 (2%)
Unknown	28 (13%)	46 (22%)	82 (38%)	19 (9%)	4 (2%)	22 (10%)	7 (3%)	5 (2%)	0 (0%)

Interventions

There were varied interventions for biotic constraints. At the point of consulting the agricultural extension officer at the plant clinic, almost half of the farmers (45%) had not initiated any intervention measures for control of pests. Although farmers, those who had attempted to control the problem prior to visiting a plant clinic, used some non-chemical control methods and occasionally applied homemade botanical (e.g. neem extract) and non-botanical (e.g. ash) pesticides (3%), pest management was mainly by the use of synthetic pesticides (insecticides and fungicides) (52%). The choice of intervention measure (including the option not to act) was most likely influenced by the time, location and problem type (Table 9). Over time, the number of farmers attempting to intervene in the management of crop pests increased leading to the heightened use of insecticides and fungicides. While only 49% of farmers failed to attempt to intervene in the management of crop pests in year one, by year four, the number had reduced to 21%. Also, more farmers in rural areas (58%), relative to their counterparts in peri-urban areas (47%), tried to manage the pests prior to visiting a plant clinic. Finally, more farmers, before visiting a plant clinic, attempted to manage mite, fungal, and insect pests, than they did for the other pest categories (e.g. nematodes) (Table 10).

Table 9. Summary of results of Multinomial Logistic Regression for relationship between test variables (time, farmers' location and gender, and problem type) and choice of pest management practice

Test variables	Chi-Square	df	Sig.
Study period	576.373	15	**<.001**
Location	23.916	5	**<.001**
Gender	.	5	**.**
Variety	.	60	**.**
Problem type	1.607E3	65	**<.001**

Table 10. Cross tabulation showing frequencies and percentages (represented in brackets) in of problem type among the various intervention measures employed in smallholder tomato production in Kenya

	Cultural	Fertilizer application	Fungicides	Insecticides	Local knowledge	None
Bacterium	50 (8)	0 (0)	241 (39)	6 (1)	6 (1)	316 (51)
Fungus	11 (1)	0 (0)	743 (66)	11 (1)	0 (0)	349 (31)
Insect	17 (1)	9 (0)	34 (2)	1073 (64)	0 (0)	570 (34)
Mite	4 (1)	0 (0)	8 (2)	275 (68)	0 (0)	117 (29)
Nematode	10 (9)	2 (2)	0 (0)	0 (0)	0 (0)	97 (89)
Nutrient deficiency	29 (5)	29 (5)	52 (9)	0 (0)	0 (0)	477 (82)
Virus	1 (1)	1 (1)	38 (26)	13 (9)	0 (0)	93 (63)
Water mould	1 (1)	1 (1)	24 (24)	1 (1)	0 (0)	74 (73)
Bird	1 (33)	0 (0)	1 (33)	0 (0)	0 (0)	1 (33)
Mammal	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	3 (100)
Phytophthora	0 (0)	0 (0)	0 (0)	1 (17)	0 (0)	5 (83)
Weed	2 (100)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Other	1 (2)	0 (0)	0 (0)	0 (0)	0 (0)	56 (95)
Unknown	0 (0)	0 (0)	5 (22)	0 (0)	0 (0)	1(78)

3.4 Discussion

3.4.1 Farm demographics

Male dominance in tomato production could be attributed to the fact, tomato production requires a lot of capital investments and, in Kenya, men compared to women have higher levels of access to human and physical capital (Quisumbing et al., 1995, Mwangi et al., 2015). In addition, production of tomato is considered a risky undertaking and women tend to be risk averse (Clottey et al., 2009). Finally, this phenomenon could also be credited to variations in the quality of land cultivated by women and men, (including topography, soil quality, and nearness to access points such as housing, water sources and roads) and shadow prices of inputs and credits, leading women's production limit to lie below men's frontier (Peterman et al., 2011).

Insufficient youth participation in tomato production could be the result of, among other things, scarcity of land (lack of land access). Land remains a challenge for most young people since a considerable number of them do not have land of their own to cultivate. Additionally, young people have limited access to improved farm inputs - aggravated by the fact they are not targeted by government-sustained input programmes; and lack viable markets and targeted extension support. Impeding participation of youth in tomato production, also, is the widespread perception that agriculture is not rewarding and the resulting benefits are long term. Stemming from this, young people tend to choose urban salaried employment than farming (Chinsinga and Chasukwa, 2012, Naamwintome and Bagson, 2013, Bezu and Holden, 2014).

The progressive decline in the area under tomato cultivation could be the result of more farmers adopting high-yielding varieties and other modern technologies which ensure increased production using less land (Odame et al., 2009). Disaffection by farmers in the cultivation of tomato may be another possible reason explaining the decline in areas under tomato cultivation. This disaffection may be the result of institutional limitations such as poor post-harvest technologies; poorly organised urban and rural market infrastructures permitting volatile price fluctuations (Geoffrey et al., 2014).

3.4.2 Access to high quality seeds

Given the array of high-yielding varieties available to smallholder farmers, and the association between adoption of improved seed and cost, limited adoption of high-yielding varieties could be the result of smallholder farmers' preference for traditional varieties, as an alternative to expensive varieties (Lunduka et al., 2012, Kassie et al., 2013). According to Kassie et al. (2013), wealthier households are more likely and able to fund the procurement of expensive inputs, including improved seeds.

Preference for determinate tomato types could be premised on the fact that indeterminate types require staking, tying and hedging during the crop cycle. These cultural practices are costly, time consuming and require more labour. In addition, farmers prefer to grow determinate types in order to have concentrated fruiting, and relatively larger fruits (Simonne et al., 2005, Fufa et al., 2009, Cantliffe et al., 2009, Gao et al., 2010). Similarly, preference for processing tomatoes over fresh market tomatoes by smallholder farmers may have had cost considerations. Compared to processing tomatoes, fresh market tomatoes have larger production cost (Boriss and Brunke, 2005, Simonne et al., 2006).

The maintenance of a wide genetic base, typified by farmers' cultivating a wide array of varieties, reduces the threat of crop loss occasioned by biotic and abiotic stressors specific to particular strains of the crop (Altieri and Koohafkan, 2008).

3.4.3 Tomato production constraints and intervention

Constraints

Consistent with previous studies, tomato production is highly limited by biotic and abiotic constraints, including diseases and insect pests (Picanço et al., 2007, Retta and Berhe, 2015). Higher incidences of insect pests, particularly migrant pests, are recorded whenever there are increases in temperature occasioned by various inter-related processes, including amplified rates of population growth, development and migration. As a result of climate change, migrant pests are colonizing new habitats. This is because, the progressive, ongoing increase in atmospheric carbon dioxide impacts pest species directly (the carbon dioxide fertilization effect) and indirectly (through interactions with other environmental factors) (Altieri and Koohafkan, 2008).

Tomato production in the study was influenced by multiple biotic and abiotic factors whose incidences varied between years, location and variety. The spatio-temporal distribution of insects could be the result of numerous factors, including their high biotic potential, the artificial selection of insecticide-resistant populations, the enormous array of their host plants (intensifying their endurance in tilled areas), and intra-continental dispersion enablement due to their ability to drift and spread quickly into a new area, and due to human transport. Moreover, the lack of natural enemies that have co-evolved could explain why changes in pest populations, particularly for migratory insect pest (such as tomato leaf miner – *Tuta absoluta*) in the newly ravaged areas are faster than in the innate area, where natural enemies are more common (Retta and Berhe, 2015, Zekeya et al.). During the study period, Africa was experiencing significant impacts from *T. absoluta* which threatened tomato production in the continent (Pratt et al., 2017).

The influence of tomato variety on pest infestation could be tied to presence/absence of genes controlling the manufacture of chemicals that kill or deter arthropod pests and pathogens (Lattanzio et al., 2006, Oliveira et al., 2009). In the natural environment, plants encounter numerous pests, and how they respond to attack by such organisms leads to tolerance or resistance mechanisms enabling the plant to survive. According to Lattanzio et al. (2006), resistance mechanisms denote characteristics that avert or reduce attack. On the other hand, tolerance mechanisms do not prevent attack, instead, they minimize or counterbalance the effects on the plant fitness by altering the plant's physiology thereby cushioning the effects of herbivory or diseases. Tolerance ordinarily encompasses some measure of compensation for pest injury. Conversely, resistance strategies include techniques that quickly clear herbivory or infection, and mechanisms that reduce the distribution of damage within the host (Lattanzio et al., 2006).

Intervention

Much as smallholder tomato farmers used some cultural control practices and sporadically some homemade botanical and non-botanical pesticides, pest management was mainly through the use of synthetic pesticides. The high dependence on synthetic pesticides could be indicative of the fact that the farmers may not have been aware of other pest control tactics that are inexpensive, effective and favourable to the environment (Sibanda et al., 2000).

The choice of intervention differed significantly between years, location and causative agent. With the passage of time, more and more farmers attempted to manage crop pests and abiotic stressors, albeit unsuccessfully. Increase in the number of farmers instituting management practices has been credited to public agricultural extension services and mass communication media. Both have been credited for introducing farmers to new technologies and farming practices (Van den Berg and Jiggins, 2007). Beyond the introduction of new technologies and farming practices to farmers, little investments may have been made in farmer education, in the wide sense of growing their abilities to comprehend, innovate and adapt to the changing dynamics. This lack of care may have led to smallholder farmers employing sub-optimal management practices which, in turn, may have resulted in increased incidences of crop pests (Van den Berg and Jiggins, 2007, Fermont et al., 2009).

The increase in incidences of certain of biotic and abiotic stressors, over time, may have led to heightened use of specific chemical pesticides to manage them (Altieri and Koohafkan, 2008).

3.5 Conclusion

There is male dominance and insufficient youth participation in the smallholder tomato production in Kenya. Coupled with this, a majority of smallholder farmers cultivate tomatoes in areas not exceeding an eighth of an acre. When it comes to the choice of tomato varieties, most smallholder farmers opt for cheaper tomato varieties. Also, there is an overwhelming preference by smallholder farmers for determinate varieties and varieties ideal for processing. Furthermore, a diverse range of constraints impede tomato production. These include pests and abiotic factors. The major groups of pests and abiotic factors impeding tomato production are insects, fungi, bacteria, nutrient deficiency, mites, virus, nematodes and water moulds. Factors influencing the occurrence of biotic and abiotic constraints include time, tomato variety and location. Finally, for the management of biotic pests, much as smallholder tomato farmers used some cultural control practices and sporadically some homemade botanical and non-botanical pesticides, pest management was mainly through the use of synthetic pesticides. The choice of intervention (including the option not to act) is mostly influenced by time, location and problem type.

Much as women in Kenya play a crucial part in satisfying the food and nutrition requirements of their families by means of food production, economic access to food, and nutrition security, they are inadequately resourced. Thus, removing constraints confronting them and granting them access to resources available to their male counterparts could significantly impact their participation in tomato production. To increase women participation in tomato production, the government, both at the national and in the devolved units, must take policy steps to increase women’s physical and human capital. This may include safeguarding women’s traditional rights to land, provision of effective agricultural extension services to women, increasing education for girls, particularly in rural areas, and supporting the training of more women in agricultural and related sciences. In addition, both national and county governments should be deliberate in increasing women’s ability to generate and control income and in protecting women’s health and nutritional status. Increasing youth participation in tomato production is equally crucial since young people are both a source of labour and a potential entrepreneurial force for job creation. Towards this, there is need to rebrand agriculture as the new uncharted territory for growth in business prospects and not as a last resort for those unable to make a livelihood elsewhere. Access to land and finance are the main factors impeding youth participation in agriculture. Consequently, efforts should be made towards motivating young entrepreneurs in agriculture through the development of financial packages tailored to varied conditions of the sector, with the government, both national and county, providing guarantee schemes that would underwrite the uncertainties surrounding such packages. In addition, the government should promote land reforms and formulation of laws that ensure young people are not disenfranchised when it comes to land ownership.

Implementing deliberate strategies of competitiveness along the crop’s value chain is crucial in poverty mitigation. This, in turn, will facilitate the transformation of tomato production from subsistence production to market-oriented production. Consequently, the government should explore public-private partnerships that enable farmers to access and fully exploit available technologies such as improved seeds and other inputs. Such partnerships would involve bulk purchasing and local manufacturing of inputs; investments in transport infrastructure corridors linking productive zones and main markets within and across the regions; creation in rural areas of partnership opportunities for market-related infrastructure investments that will integrate smallholder farmers into local and export value chains; and encouragement of private investment in market-related infrastructure to hasten integration of smallholders into the value chain.

The high proportion of smallholder farmers attempting to control crop pests shows they are cognizant of the losses attributed to biotic stressors. The predominant management practice reported by the smallholders was the application of synthetic pesticides. However, in applying synthetic pesticides, smallholder tomato farmers appeared unable to distinguish pest control chemicals (particularly for the management of pathogens). Diversification of management strategies is likely to improve the effectiveness of control and perhaps lead to the reduction in the costs associated with managing biotic and abiotic stressors. Smallholder tomato farmers, therefore, need to know an array of management options, including their appropriate handling and usage.

CHAPTER 4

INFLUENCE OF AGRO-ECOLOGOCAL ZONES ON THE DISTRIBUTION PATTERNS OF ARTHROPOD PESTS

4.1 Introduction

Tomato (*Solanum lycopersicum*) is a popular food crop cultivated and consumed worldwide (Gogo et al., 2012, FAOSTAT, 2018). In Kenya, the crop, cultivated in almost every homestead for home consumption, serves as an important cash crop for both small - and medium – scale commercial farmers, and as an important source of vitamins (Gogo et al., 2012). In addition to vitamins, tomato is also rich in antioxidants, including lycopene, carotenoids, phenolics and ascorbic acid, which can play an important role in averting cardiovascular diseases and cancer (Toor and Savage, 2005, Kirsh et al., 2006, Oduor, 2016)

Tomato thrives under warm conditions (Oduor, 2016). The ideal soil temperature for seed germination is 20^0C or above; below 16^0C germination is extremely slow. The optimal daily maximum air temperature for vegetative growth, fruit set and development is between 25^0 and 35^0C (Hartz et al., 2008). With sufficient soil moisture, tomato plants can withstand temperatures well in excess of 38^0C, though the fruit set can be severely reduced. Fruit development and quality are adversely affected when night and day temperatures fall below 10^0 and 20^0C, respectively (Hartz et al., 2008).

The crop thrives under a variety of soil textures (Hartz et al., 2008, Oduor, 2016). Suitable soil textures range from sandy to fine-textured clay soil, provided it is well aerated, has a good structure, and is properly drained (Diver et al., 1999, Hartz et al., 2008).

In recent years, the growth rate of tomato production in Kenya has increased (FAOSTAT, 2018). Yields, however, continue to remain low due to a myriad of constraints. Key agronomic challenges faced in tomato production, as identified in chapter 3, include incidences of arthropod pests (insects, mites and nematodes), diseases (fungi, bacteria and viruses) and physiological disorders (caused by non-pathological conditions such as drought, cold, heat and salinity) (Umeh et al., 2002, Anastacia et al., 2011, Asgedom et al., 2011, Toroitich et al., 2014, Oduor, 2016).

Among the factors in the tropics that favour build-up of arthropod pests include climate change, and the existence of complex agroecosystems and diverse agricultural systems in the tropics (Hill, 1983, Gornall et al., 2010).

According to Tylor et al. (2018), many ecological patterns are heavily dependent on phenology, and this continues to evolve in many animals and plants. For instance, increased temperatures have reduced the overwintering mortality of aphids which in turn has enabled their widespread dispersion (Gornall et al., 2010). Lepidopterans fly earlier, exhibit longer and expand their geographic range (Taylor et al., 2018). Aphids and weevil larvae respond positively to elevated carbon dioxide concentration, and locusts migratory patterns being influenced by rainfall patterns (Gornall et al., 2010).

Changes in phenology from time to time reflect the changes occurring in the biosphere (Taylor et al., 2018). However, a useful question to ask is whether these variations in phenology are linked in a way permitting the interaction between plants and animals to remain relatively stable amidst the changes in time. This paper thus seeks to establish ecological limits of major arthropod pests of tomato in smallholder agriculture subsector of Kenya by (1) cataloguing major arthropod pests of tomato in Kenya, (2) determining the major arthropod pests of tomato in Kenya distribution patterns in relation to time and agro-ecological zonation

4.2 Materials and methods

4.2.1 Study overview

This study examined data collected from plant clinics in 121 locations over a four-year period (June 2013 to May 2017). The 121 locations where the data were collected were distributed in 14 counties of Kenya: Nyeri, Kirinyaga, Embu, Tharaka Nithi, Machakos, Kiambu, Nakuru, Trans Nzoia, Bungoma, Elgeyo Marakwet, Kajiado, Siaya, Narok and West Pokot. The range of these locations represented 18 different production potentials (Agro-ecological zones) (Table 11).

Table 11. Agro-ecological zones in the study area

Agro-Ecological Zone	Average Altitude in m	Annual average mean temperature in ^{0}c	Annual average Rainfall in mm
Upper Highland Zones (humid) – UH1	2,250 – 2,755	14.9 – 11.7	1,245 – 1,788
Upper Highland Zones (sub humid) – UH2	2,290 – 2,670	14.9 – 12.9	1,413 – 1,904
Lower Highland Zones (humid) – LH1	1,904 – 2,226	17.2 – 15.1	1,364 – 1,669
Lower Highland Zones (sub humid) – LH2	1,908 – 2,256	17.5 – 15.2	1,082 – 1,329
Lower Highland Zones (semi-humid) – LH3	1,942 – 2,196	17.1 – 15.4	885 – 1,105
Lower Highland Zones (transitional) – LH4	1,783 – 1,977	17.8 – 16.6	823 - 953
Lower Highland Zones (semi-arid) – LH5	1,980 – 2,040	16.2 – 15.7	650 - 850
Upper Midland Zones (humid) – UM1	1,578 – 1,802	19.3 – 18.0	1,355 – 1,675
Upper Midland Zones (sub humid) – UM2	1,523 – 1,755	19.7 – 18.3	1,140 – 1,410
Upper Midland Zones (semi-humid) – UM3	1,425 – 1,675	20.2 – 18.7	990 – 833
Upper Midland Zones (transitional) – UM4	1,477 – 1,704	20.0 – 18.7	983 – 1,173
Upper Midland Zones (semi-arid) – UM5	1,446 – 1,677	20.3 – 18.7	608 – 760
Upper Midland Zones (arid) – UM6	1,500 – 1,770	19.9 – 17.7	500 – 650
Lower Midland Zones (sub humid) – LM2	1,337 – 1,457	21.4 – 20.7	1,419 – 1,594
Lower Midland (semi-humid) – LM3	1,158 – 1,312	22.1 – 21.1	970 – 1,158
Lower Midland Zones (transitional) – LM4	1,114 – 1,297	22.3 – 21.2	786 – 904
Lower Midland Zones (semi-arid) – LM5	939 – 1,238	23.4 – 21.7	692 – 803
Lower Midland Zones (arid) – LM6	1,200 – 1,300	21.5 – 20.9	400 - 500

Source**:** (Jaetzold and Schmidt, 1983)

During the period under review (June 2013 to May 2017), a total 37,051 smallholder farmers visited plant clinics in 121 locations. Of these, 4,907 were farmers cultivating tomatoes. And of the farmers cultivating tomatoes, 2,189 of them had problems relating to arthropod pests.

4.2.2 Data management system

For this study, data management workflow, which included data collection, was broken down into stages. Table 12 shows the data management stages and those responsible.

Data collection

In data collection, the Plantwise prescription form (Figure 3) was used by plant doctors to capture particulars of farmers' queries. Besides the farmers and the plant clinic details, the plant doctors recorded information regarding the crop, symptoms and diagnoses, and pest management practices. Upon completion, the prescription forms were collated and couriered to the data hub located in Nairobi. The process of entering data was undertaken using an Excel-based tool mimicking the layout of the Plantwise prescription form. For storage, the data was entered into the restricted section within the Plantwise knowledge bank called Plantwise Online Management System (POMS). POMS serve as a focal resource for the management of plant clinic data.

Table 12. Stages in the data management system process and actors involved

Data management system category	Data management system step	Actors involved
Data collection	1. Recording	Plant doctors
	2. Transfer	Plant doctors, via data entry hubs
	3. Data entry	Data clerks
Data processing	4. Harmonization	Researcher
	5. Validation	Researcher.
Data use	6. Analysis	Researcher

Data processing

Harmonization of plant clinic data involved the cleaning of data (location details, plant doctor names, crop names and diagnoses). This was done by the researcher.

Data validation

At a plant clinic, a field diagnosis is based on signs and symptoms observed on the plant sample, combined with information gained from farmer. Plant doctors have access to hand lens/microscope to observe some of the smaller features.

Additionally, plant doctors have access to diagnostic photosheets which offer pictorial guidance for diagnosing pests on crops. Symptom descriptions on the photosheets help the 'plant doctors' distinguish between similar problems.

At data validation stage, the researcher reviewed all the 2,189 plant clinic records to check the accuracy of the diagnoses. Validating diagnoses was done by checking that: (1) a diagnosis was recorded in the form; (2) it was specific to at least sub-group level (e.g. mites, mealybugs, thrips, etc.); (3) it was plausible (i.e. known to affect the host crop and has previously been reported in the country); (4) key symptoms of the diagnosed pest were recorded and; (5) it was definitive (symptoms were not easily confused with other causes); and (6) the picture of the sample accompanying the record confirmed the diagnosis.

Data analysis

Analysis of the data was carried out by means of a statistical program, SPSS, version 16. The analyses ran included looking at trends over time, and reviewing recommendations from prescription forms. To gauge the comparative frequency of variables, cross tabulation was used and tested for significance by the Pearson Chi-square test. Associations between nominal dependent variables (seed variety, pest type and pest management intervention) and many independent variables were examined using multinomial logistic regression, and Goodness-of-fit test used to examine how well the model fits the data. Student's t-test and ANOVA were used to compare group means. Significance was defined as a p value ≤ 0.05.

4.3 Results

4.3.1 Arthropod pests of tomato in Kenya

A diverse range of arthropod pests hamper tomato production in Kenya. A total of 10 species belonging to 7 orders were reported as major arthropod pests of tomato in Kenya (Figure 6). The primary arthropod pests attacking tomato seedlings were cutworms (*Agrotis* spp.) (CW). General foliage and fruit feeders were tomato leafminer (*T. absoluta*) (TA), whiteflies (*Bemisia tabaci*) (WF), spider mites (*Tetranychus* spp.) (SM), African bollworm (*Helicoverpa armigera*) (ABW), leafminers (*Liriomyza* spp.) (LM), thrips (*Frankliniella* spp.) (TH), aphids (*Aphis gossypii, Myzus persicae*) (AP), and mealybugs (*Planococcus* spp.) (MB)

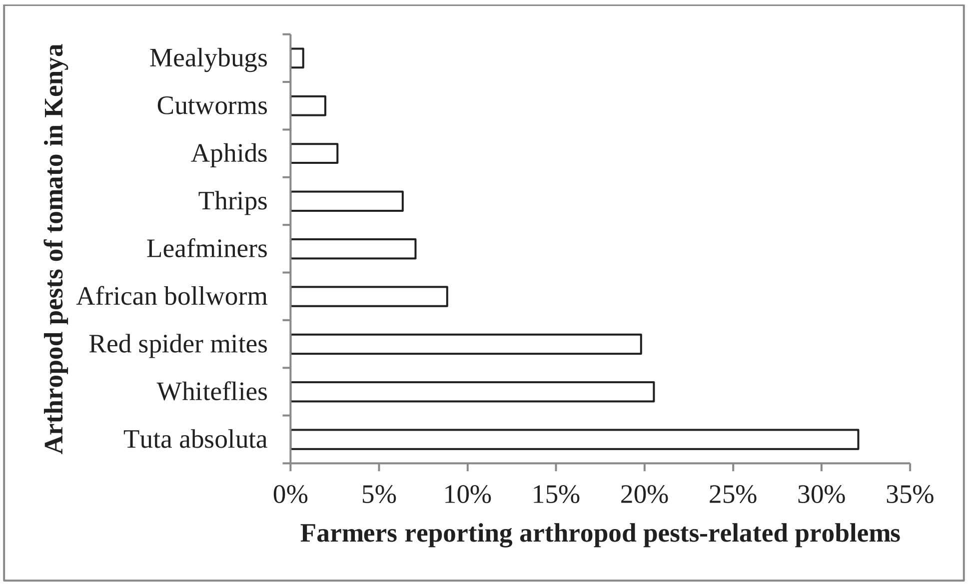


Figure 6. Diversity of arthropod pests of tomato in Kenya

It is more likely that the incidence of these pests was influenced by time and agro-ecological zonation (Table 13). Frequencies of arthropod pests showed considerable inter-year differences (Figure 7) with more cases of spider mites and whiteflies being recorded in first year of the study than any other arthropod pest. For *T. absoluta*, after the first year of the study, there were more recorded cases of the pest than any other arthropod pest.

Table 13. Summary of results of Multinomial Logistic Regression for relationship between test variables (study period, AEZs, tomato variety, and plant growth type) and incidences of pests

Test variables	Chi-Square	df	Sig.
Study period	241.220	27	**<.001**
Agro-ecological zones	451.420	153	**<.001**
Goodness-of-Fit (analysis)	3131.252	3294	.979

4.3.2 Distribution of arthropod pests of tomato in relation to agro-ecological zonation

There was considerable variation in composition and frequency of arthropod pests in different agro-ecological zones (AEZs). Most of the arthropod pests reported were associated with upper and lower midland zones while only a few were reported in upper highland zones (Table 14). AEZs (belts) that reported the highest diversity of arthropod pests were LH2, LH3, LM4 and UM3 while UH2 recorded the least diversity. Among the arthropod pests, whiteflies, spider mites, leafminers and *T. absoluta* were cosmopolitan in distribution, registering a presence in all or nearly-all of the study's AEZs. In terms of frequency (Table 15), there were more cases of spider mites, cutworms and thrips that were reported in lower highland AEZs than in the other AEZs. Also, compared to the other AEZs, there were more cases of African bollworm, aphids, leafminers, and whiteflies that were reported in upper midland AEZs than in the other AEZs. On the other hand, cases of *Tuta absoluta* and mealybugs were mostly pronounced in the lower midland zones.

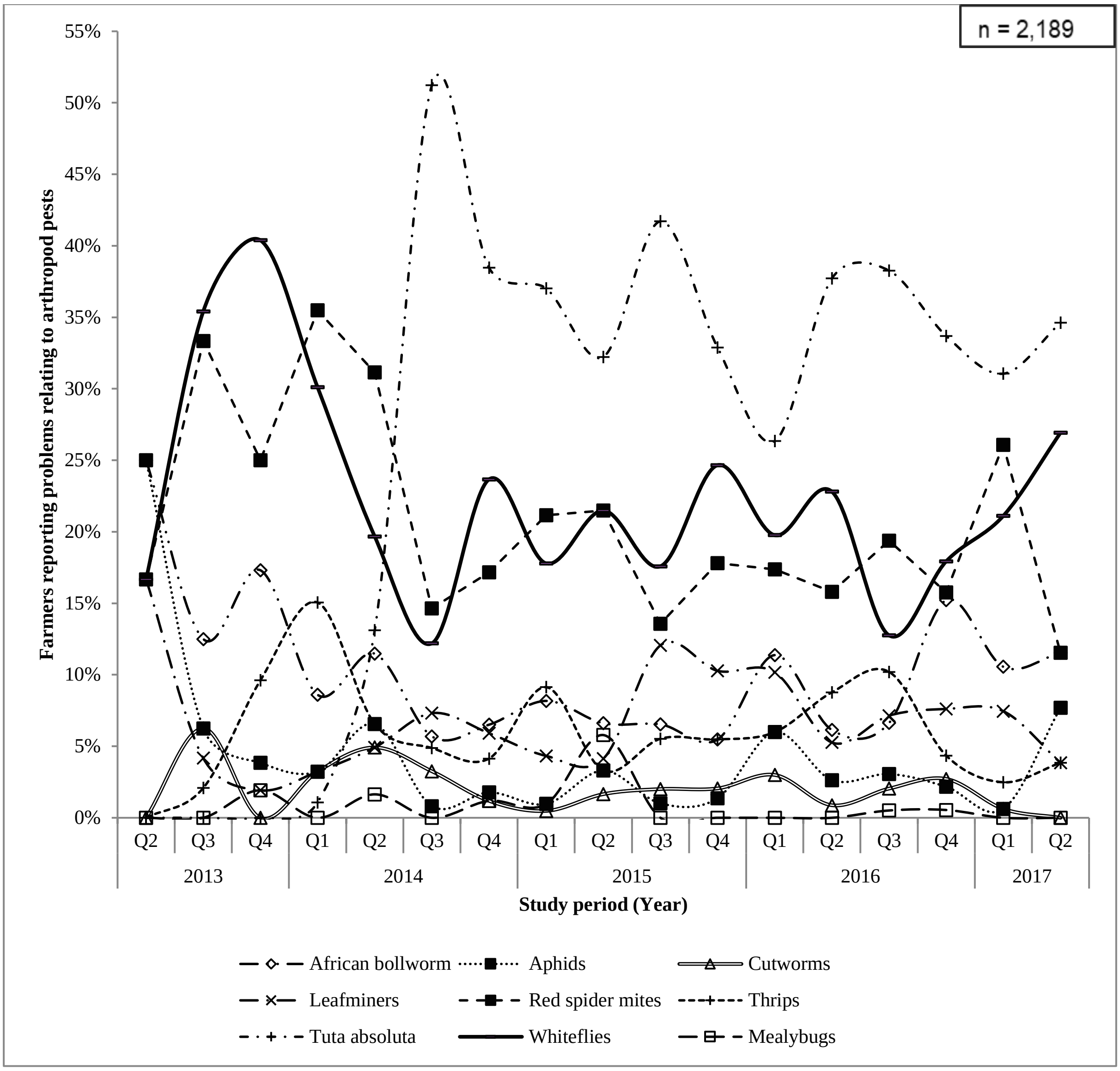


Figure 7. Distribution of arthropod pests of tomato over time

Table 14. Incidences of arthropod pests (presence-absence) reported in the different agro-ecological zones of Kenya

AEZs (belts)	ABW	AP	CW	LM	SM	TH	TAb	WF	MB
UH1	+	0	0	+	0	+	0	+	0
UH2	0	0	0	+	+	0	0	+	0
LH1	0	0	0	+	+	0	+	+	0
LH2	+	+	+	+	+	+	+	+	+
LH3	+	+	+	+	+	+	+	+	+
LH4	0	+	0	+	+	0	+	+	+
LH5	0	0	0	0	+	0	+	+	0
LM2	+	0	0	0	+	+	+	+	0
LM3	+	+	0	+	+	+	+	+	0
LM4	+	+	+	+	+	+	+	+	+
LM5	+	+	+	+	+	0	+	+	+
LM6	+	+	0	+	+	+	+	+	+
UM1	+	+	+	+	+	+	+	+	0
UM2	+	+	0	+	+	+	+	+	0
UM3	+	+	+	+	+	+	+	+	+
UM4	+	+	+	+	+	+	+	+	0
UM5	+	+	+	+	+	0	+	+	+
UM6	+	+	0	+	+	0	+	+	0
n	184	55	41	147	412	132	667	427	15

Key: + = Present; 0 = Absent; ABW = African bollworm; AP = Aphids; CW = Cutworms; LM = Leafminers; SM = Spider mites; TH = Thrips; TAb = *Tuta absoluta*; WF = Whiteflies; and MB = Mealybugs

Table 15. Cross tabulation showing frequencies and percentages (represented in brackets) of arthropod pests in the various AEZs

AEZs	ABW	AP	CW	LM	SM	TH	TAb	WF	MB
LH1	0 (0)	0 (0)	0 (0)	1 (1)	3 (1)	0 (0)	4 (1)	3 (1)	0 (0)
LH2	24 (13)	2 (4)	1 (2)	3 (2)	63 (15)	13 (10)	29 (4)	16 (4)	2 (13)
LH3	13 (7)	9 (16)	19 (46)	21 (14)	89 (22)	45 (34)	132 (20)	97 (23)	1 (7)
LH4	0 (0)	1 (2)	0 (0)	1 (1)	8 (2)	0 (0)	7 (1)	8 (2)	1 (7)
LH5	0 (0)	0 (0)	0 (0)	0 (0)	10 (2)	0 (0)	5 (1)	5 (1)	0 (0)
LM2	1 (1)	0 (0)	0 (0)	0 (0)	3 (1)	4 (3)	4 (1)	3 (1)	0 (0)
LM3	4 (2)	6 (11)	0 (0)	3 (2)	15 (4)	4 (3)	89 (13)	11 (3)	0 (0)
LM4	15 (8)	5 (9)	3 (7)	27 (18)	55 (13)	14 (11)	96 (14)	56 (13)	3 (20)
LM5	13 (7)	2 (4)	6 (15)	9 (6)	10 (2)	0 (0)	39 (6)	5 (1)	2 (13)
LM6	2 (1)	3 (5)	0 (0)	3 (2)	14 (3)	12 (9)	28 (4)	8 (2)	3 (20)
UH1	1 (1)	0 (0)	0 (0)	1 (1)	0 (0)	1 (1)	0 (0)	3 (1)	0 (0)
UH2	0 (0)	0 (0)	0 (0)	1 (1)	2 (0)	0 (0)	0 (0)	1 (0)	0 (0)
UM1	6 (3)	1 (2)	1 (2)	1 (1)	5 (1)	1 (1)	14 (2)	9 (2)	0 (0)
UM2	12 (7)	2 (4)	0 (0)	7 (5)	20 (5)	7 (5)	21 (3)	14 (3)	0 (0)
UM3	39 (21)	13 (24)	5 (12)	28 (19)	43 (10)	12 (9)	95 (14)	99 (23)	2 (13)
UM4	43 (23)	7 (13)	4 (10)	17 (12)	44 (11)	19 (14)	54 (8)	56 (13)	0 (0)
UM5	5 (3)	2 (4)	2 (5)	10 (7)	12 (3)	0 (0)	29 (4)	10 (2)	1 (7)
UM6	6 (3)	2 (4)	0 (0)	14 (10)	16 (4)	0 (0)	21 (3)	23 (5)	0 (0)
n	184 (100)	55 (100)	41 (100)	147 (100)	412 (100)	132 (100)	667 (100)	427 (100)	15 (100)

Key: ABW = African bollworm; AP = Aphids; CW = Cutworms; LM = Leafminers; SM = Spider mites; TH = Thrips; TAb = *Tuta absoluta*; WF = Whiteflies; and MB = Mealybugs

4.4 Discussion

4.4.1 Arthropod pests of tomato in Kenya

Consistent with previous studies, a diverse range of arthropod pests were found to hamper tomato production in Kenya. Despite variations in arthropod pests' frequency, *T. absoluta*, whiteflies and spider mites were the most dominant pest species, confirming their major pest status on tomatoes as earlier reported by Oduor (2016) and Zekeya et al. (2017).

T. absoluta is an invasive pest of tomato native to South America (Tropea Garzia et al., 2012). According to Tonnang et al. (2015), surveys carried out in various places in Africa have demonstrated that *T. absoluta* is rapidly spreading across the continent. This meteoric spread could be credited to the widespread cultivation and movement of tomato fruits across the border through trade. Additionally, the climatic and ecological conditions of the continent mirror those of South America countries (Tonnang et al., 2015). *T. absoluta* was first reported in Kenya in 2014 (Gebremariamd, 2015). This report tallies with the research findings where the pest appeared for the first time in the study area in the second year of study (2014). Subsequently, higher incidences of *T. absoluta* are recorded, possibly, due to the pest's high biotic potential (Zekeya et al., 2016). The pest is a multivoltine species, exhibiting a high reproductive potential that allows its population to increase rapidly (Tropea Garzia et al., 2012). In addition, *T. absoluta* has a wide host range that allows it, when tomato is scarce, to switch to other available host in order to sustain its population and recover when tomato is in plenty (Zekeya et al., 2016). Another advantage *T. absoluta* possesses is its ability to tolerate and adapt harsh conditions such as dry conditions, extreme cold and hot environments (Zekeya et al., 2016). Like *T. absoluta*, whitefly also has high reproductive potential (Salas and Mendoza, 1995). Coupled with this, the pest has unique life habits that enable it to transmit viral diseases and cause severe damage through plant feeding (Salas and Mendoza, 1995). Spider mites, like *T. absoluta*, are invasive pests, native to South America (Migeon et al., 2009). Over the years, spider mites have become one of the most severe pests of tomato in Africa, resulting in significant losses in south-east Africa and west Africa (Migeon et al., 2009).

The findings of this study are in agreement with other studies on the effects of host plants on pest infestation (Kamara et al., 2007, Akköprü et al., 2015). According to Akköprü et al. (2015), plants influence host choice and the acceptance by arthropod pests with their biochemical, nutritional and morphological features.

4.4.2 Distribution of arthropod pests of tomato in relation to agro-ecological zonation

There was considerable variation in composition and frequency of infestation of arthropod pests in the different AEZs. This phenomenon could be credited to the fact that altered weather patterns increase or decrease crop vulnerability to pest infestations (Rosenzweig et al., 2001). According to Rosenzweig et al. (2001), the spatio-temporal distribution and proliferation of arthropod pests is controlled by climate.

In light of the foregoing, it is not surprising that most of the arthropod pests were reported in upper and lower midland zones, as opposed to the upper highland zones. Upper and lower midland zones are characterized by high temperatures and moderate precipitation. On the other hand, highland zones are characterized by low temperatures and excessive precipitation. Precipitation – whether insufficient, excessive, or optimal – is perhaps the most crucial variable affecting pest-crop interactions(Rosenzweig et al., 2001). The effects of moisture stress on crops predispose them to damage by pests, particularly in the early stages of plant development. In addition, moisture influences fecundity and speed of development of most arthropod pests (Rosenzweig et al., 2001). The predisposition to excessive moisture, however, can prove harmful to arthropod pests' population through encouraging pathogens such as fungi, mycoplasma and bacteria, thus causing mortality among arthropod pests. Also, excessive moisture may adversely affect the normal feeding and development activities of arthropod pests (Alto and Juliano, 2001, Atwal, 2014). When it comes to temperature, arthropod pests are sensitive to it due to the fact they are cold-blooded (Rosenzweig et al., 2001). Increases in temperature, for instance, may lead to changes in arthropod pests' population growth rates, changes in the pests' geographical distribution, changes in crop-pest synchrony, proliferations in pests' generations, and increased invasion of migrant pests (Porter et al., 1991). Extremely high temperature, however, reduce arthropod pests longevity (Rosenzweig et al., 2001).

In the study, whiteflies, spider mites, leafminers and *T. absoluta* exhibited cosmopolitanism, registering a presence in all or nearly-all of the study's AEZs. This finding indicates that the aforementioned pests are widely spread in their distribution in Kenya, aided by their capacity to endure and adapt in severe conditions such as hot environments, dry conditions and extreme cold (Kang et al., 2009, Skaljac et al., 2010, Migeon et al., 2010, Zekeya et al., 2016).

4.5 Conclusion

From this study, the key arthropod pests of tomato can be categorized into fruit borers, leaf feeders, leaf miners, cut worms, phloem feeders and gall producers. Among the arthropod pests, *Tuta absoluta*, whiteflies and spider mites are emerging as major threats to sustainability of tomato production. Changes in frequency and spatial patterns of arthropod pests are related to agro-ecological zonation. With climate change in perspective, future consequences for the performance of arthropod pests will certainly depend on the degree and character of climate change in the various AEZs and the quality of specific natural communities. AEZs representing upper distribution limits, such as the upper highlands, will possibly be impacted most by rise in temperature and enhanced developmental conditions of, for instance, aphids, cutworms, *T. absoluta* and mealybugs. On the other hand, the increase in temperature and drought will possibly result in shifts and range contractions of arthropod pests that are less tolerant to heat. In view of these future challenges and probable risks, crop protection practitioners need effective measures developed on account of comprehensive planning and decision-making. Towards this end, monitoring tools and the incorporation into comprehensive pest management planning systems of essential pest risk assessment or simulation models become important.

For the management of arthropod pests, this study provides valuable insights into practices used in the management of arthropod pests in tomato production in Kenya. High risk pesticides continue to be used by smallholder farmers in tomato production. In light of the foregoing, there is growing consensus on the need for reduction in agricultural pesticide use or risk, and IPM has been identified as a means to achieve this end. However, viable as IPM is as a concept, appealing to a cross-section of interest groups, it is unlikely that IPM will result in pesticide reduction among smallholder farmers. This is because, providing smallholder farmers with economical, non-risky pest management alternatives requires greater sustained institutional support than is presently available. Alternative management procedures to the use of high toxic synthetic pesticides, and better assessments of potential profit-loss to a smallholder for application and non-application of high toxic synthetic pesticides are required. Crops bred for resistance could potentially reduce over-reliance in high toxic synthetic pesticides. However, for long-term effectiveness, development of resistance varieties must be developed within the confines of sustainable agriculture.

CHAPTER 5

CURRENT PRACTICES FOR MANAGEMENT OF ARTHROPOD PESTS OF TOMATO IN KENYA

5.1 Introduction

Agriculture is the most important enterprise in most African countries, with low agricultural productivity exacerbating poverty, food insecurity and malnutrition (NEPAD, 2013, AGRA, 2014). Within the continent, the population involved in agriculture stands at 530 million people, and is projected to surpass 580 million by 2020 (NEPAD, 2013). In Kenya, the agricultural sector generates a quarter of its gross domestic product (GDP), accounts for 18 percent of formal employment and roughly 60 percent of informal employment (Njagi et al., 2014). Hence, agriculture not only remains an integral factor of Kenya's economy, but also remains crucial as a major source of income for the majority of its population (Wobst, 2005, Thurlow et al., 2007).

The sustainability of some agrarian systems in Africa, however, remains threatened by several factors: the effects of climate change, and population increase, which exerts pressure on land resources (NEPAD, 2013). Additionally, productivity of crops is at risk due to proliferation of crop pests (Oerke, 2006, Guenat, 2014), and the unbridled use of pesticides for their management (Bekele et al., 2013). For instance, it has been reported that, half of the smallholder producers in Kenya use more than three times the prescribed volumes of pesticides (Bekele et al., 2013). This unrestricted use of pesticides gives rise to potential health risks to both growers and consumers, and a risk to the environment.

Integral to addressing the aforementioned challenges is the role performed by properly designed and implemented agricultural advisory services (Evenson and Mwabu, 1998, Muyanga and Jayne, 2006, GoK, 2010). By definition, agricultural extension and advisory services are defined as systems that facilitate the access of farmers, their organizations and other value chain and market actors to knowledge, information, and technologies, presented in a systematic, participatory manner, with the objective of improving their production, income and (by implication) quality of life (Muyanga and Jayne, 2006, Grange et al., 2010, AGRA, 2013).

This study assessed farmers and extension agents' current practices for management of arthropod pests of tomato in Kenya and the factors influencing the same. The study uses a case study of Plantwise to answer the following research questions:

(1) What are the current practices being used by farmers for the management of arthropod pests of tomato in Kenya?

(2) What influence do individual moderators (extension officers' age, gender, education level and location) have on pest management practices prescribed by frontline agricultural extension officers to smallholder farmers?

5.2 Materials and Methods

5.2.1 Case study overview

This study examined data collected from plant clinics over a 2 year period (from 2012 to 2013) (study's legacy data). The 58 locations where the data were collected were distributed in 12 counties in Kenya: Nyeri, Kirinyaga, Embu, Tharaka Nithi, Machakos, Kiambu, Nakuru, Trans Nzoia, Bungoma, Elgeyo Marakwet, Kajiado, and West Pokot. Reflecting on their agricultural importance, the 12 counties account for only 11 percent of total land in Kenya, but for 23 percent of arable land.

Data management system

The plant clinic data collection and management workflow were broken down into stages. Table 16 shows stages in the data management system process and actors involved.

Table 16. Stages in the data management system process and actors involved

Data management system category	Data management system step	Actors involved
Data collection	1. Recording	Plant doctors
	2. Transfer	Plant doctors, via data entry hubs
	3. Data entry	Data clerks
Data processing	4. Harmonization	National data manager
	5. Validation	National Data Validation (NDV) team consisting of technical experts from national level research institutes, government ministerial representatives and technical-content experts from CABI.
Data use	6. Analysis	Research and government institutes, MOALF, CABI
	7. Sharing	'Plant doctors', research and government institutes, CABI

Data collection

In data recording, plant doctors used the Plantwise prescription form to record details of farmers' queries. In addition to basic details of the plant clinic and the farmer, the plant doctors captured information about the crop, symptoms and diagnosis and pest control tactics. Once completed by the plant doctors at the plant clinics, the prescription forms were collated, and using a courier service, sent to the central repository located at the MoALF – Plant Protection Services Division (PPSD), Kabete. Data entry was carried out using a simple Excel-based form that mimics the layout of the paper prescription form. These data were then entered in the Plantwise Online Management System (POMS) - an access-controlled section within Plantwise knowledge bank that serves as a central resource for managing plant clinic data as well as program monitoring.

Data processing

Data harmonization concerned the cleaning of digitized data (clinic details, plant doctor names, crop names and diagnoses were mandatory fields to harmonize). This was done by the program's national data manager.

Data validation (assessment of quality of diagnoses and advice) was done by a National Data Validation (NDV) team consisting of technical experts from national level research institutes, government ministerial representatives and technical-content experts from CABI. During this stage, the pest management advices were post-stratified as Integrated Pest Management (IPM) and non-IPM recommendations depending on their adherence to IPM practices. The components of IPM technology that were considered (based on their availability and affordability) were: (1) crop rotation; (2) use of certified seeds/planting material/resistant/tolerant varieties; (3) observation of planting season/appropriate planting time; (4) monitoring in seedling /field stage; (5) field sanitation/removal of volunteers and alternative hosts of pests and diseases/ removal and destruction of affected plant parts; and (6) field application of low-toxicity synthetic pesticides/commercial formulations of botanical pesticides/selective, pest-targeted pesticides/use of biological control agent. An index was developed - taking cognizance of the above mentioned six components - to categorize the pest management practices. Scores were assigned to each component based on the extent of its use: 2 = completely used; 1 = partially used; and 0 = not used at all. Consequently, a recommendation containing all the six components (in their entirety) had a score of twelve. Conversely, a recommendation lacking any of the six components had a score of zero. The score 6 was set to delineate the pest management practice as IPM or non-IPM based recommendation. To answer research questions one and two, abiotic causes data were omitted.

5.2.2 Plant doctors involved in the study

A total of 70 individual plant doctors (out of a total of 112 plant doctors) were involved in the study intended at answering research questions two. The plant doctors considered for this study were those who had submitted more than 20 plant clinic records (pre-determined threshold) during the period under review. Demographic and situational data for the plant doctors was collected including, age, gender, educational level and their location. The 70 plant doctors making up the sample were all under the age of 60, with 11% of them being below 40 years, 30% between 40 and 50 years, and 59% over 50 years. Male plant doctors constituted 64% of the sample while female plant doctors made up 36%. Of the 70 extension officers, only 87% provided information about their highest level of education with 57% having a college certificate and another 43% having a college diploma. Finally, most of the plant doctors (36%) operated plant clinics in Mount Kenya region (Embu, Tharaka Nithi, Kirinyaga and Nyeri counties) while 26% operated plant clinics in Western region (Bungoma, Trans Nzoia, Elgeyo Marakwet and West Pokot counties), 22% in Central rift (Nakuru county) and 11% in Nairobi metropolitan region (Machakos, Kiambu and Kajiado counties).

5.2.3 Data analysis

All analysis was carried out using a statistical program, SPSS, version 18. To determine the relationship between the test variables and the dependent variable, cross tabulation was used and tested for significance by the Pearson Chi-square test while the magnitude of relationships was measured by Cramer’s V statistic. Significance was defined as p value ≤ 0.05. For research question one, the dependent variable was type of pest management practices prescribed by extension workers while the test variables were plant doctors’ age, education level, gender and location. Similarly, for research question two the dependent variable was type of pest management practices prescribed by extension workers. However, the test variables for research question two were crop type and type of causative agent. In addition to determining the relationship in research questions one and two, cross tabulation was also used and tested for significance by the Pearson Chi-square test when it came to establishing the relationship between incidences of biotic and abiotic stressors and study period, location and crop type. Correspondingly, Cramer’s V statistic was also used to measure the magnitude of the relationship in this instance.

5.3 Results

5.3.1 Smallholder farmers' practices on management of arthropod pests of tomato

At the point of consulting the agricultural extension officer at the plant clinic, 57% of the farmers had not initiated any intervention measures for control of arthropod pests. On the other hand, of the farmers who had attempted to manage arthropod pests, albeit unsuccessfully, 42% applied pesticides (mostly synthetic pesticides) while a paltry 1% employed cultural practices.

A total of 43 active ingredients (AIs) were identified to be used by smallholder tomato farmers for the management of arthropod pests (Table 17). The identified AIs differed in terms of their overall hazard level: 8 of the AIs met one or more of the highly hazardous pesticides (HHP) criteria; 18 AIs were classified as “Danger” (at least one of the related human health hazard statements specified that AI is “fatal if inhaled” or “toxic”); 13 AIs were classified as “Warning”; and 2 AIs were classified as “Low hazard” (there were no known human health hazard statements related with AI).

The AIs identified to be HHPs are listed in Table 18. Of the HHPs identified, 5 out of 8 were carcinogens, 5 were known/presumed/suspected human reproductive toxicants and none causes heritable mutations in the germ cells of humans. Additionally, none of the AIs is POP listed in the Stockholm Convention and none is currently listed in the Rotterdam database of notifications of final regulatory action. 7 of 8 AIs are included in the PAN HHP list (2015). On an AI basis, all the 8 AIs are allowed for use in the EU (Approved = 8).

Of the farmers applying synthetic pesticides for the management of arthropod pests, slightly over 60% used a pesticide product that is highly toxic by at least one route of exposure (Figure 8). It is more likely that the choice to intervene (including on application of pesticides or use of cultural practices) or not to intervene was influenced by the type of arthropod pest, time and the location of the farmer (Table 19). Over time, the number of farmers opting to consult extension agents before attempting to manage arthropod pests increased from 47% (2013) to 65% (2017).

Table 17. List of active ingredients used by smallholder farmers for the management of arthropod pests in Kenya

Pesticide Active Ingredients	Chemical class	Use type	Hazard summary
Abamectin	Fumigant	Insecticide/miticide	HHP
Acephate	Macrocyclic Lactone - avermectin	Insecticide	Danger
Acetamiprid	Neonicotinoid	Insecticide/miticide	Danger
Alpha-cypermethrin	Pyrethroid	Insecticide	Danger
Azadirachtin		Insecticide/nematicide	Warning
Azoxystrobin	Strobilurin	Fungicide	Warning
Beta-cyfluthrin	Pyrethroid	Insecticide	HHP
Bifenthrin	Pyrethroid	Insecticide	Danger
Carbaryl	Carbamate	Insecticide	HHP
Carbosulfan	Carbamate	Insecticide/miticide	Danger
Chlorantraniliprole	Pyrazole/ diamide	Insecticide	Low hazard
Chlorpyrifos	Organophosphorous	Insecticide	Danger
Cyhalothrin	Pyrethroid	Insecticide	Danger
Cymoxanil	Cyanoacetamide oxime	Fungicide	Danger
Cypermethrin	Pyrethroid	Insecticide	Danger
Deltamethrin	Pyrethroid	Insecticide	Danger
Diafenthiuron	Thiourea	Insecticide/ miticide	Danger
Diazinon	Organophosphorous	Insecticide	HHP
Dimethoate	Organophosphorous	Insecticide	Danger
Dimethomorph	Morpholine	Fungicide	Low hazard
Emamectin Benzoate		Insecticide/miticide	Danger
Fenpyroximate	Pyrazolium	Insecticide/miticide	Danger
Flubendiamide	Benzene-dicarboxamide	Insecticide	Warning
Fluopicolide	Benzamide	Fungicide	Warning
Homemade botanical pesticide	Unclassified	Insecticide	Warning
Homemade non-botanical pesticide	Unclassified	Insecticide	Warning
Imidacloprid	Neonicotinoid	Insecticide	Warning
Lambda-cyhalothrin	Pyrethroid	Insecticide	Danger

Pesticide Active Ingredients	Chemical class	Use type	Hazard summary
Lufenuron	Biochemical biopesticides - insect growth regulators	Insecticide	Warning
Malathion	Organophosphorous	Insecticide/miticide	HHP
Mancozeb	Dithiocarbamate	Fungicide/Oomycide	HHP
Metalaxyl	Phenylamide	Fungicide	Danger
Methomyl	Metabolite`	Insecticide/miticide,	HHP
Profenofos	Organophosphorous	Insecticide	Danger
Propamocarb hydrochloride	Carbamate	Fungicide	Warning
Propineb	Carbamate	Fungicide	HHP
Spiromesifenw	Tetronic acid	Insecticide	Warning
Spirotetramat	Tetramic acid	Insecticide	Warning
Sulphur	Inorganic compound	Insecticide/miticide/ fungicide	Warning
Thiamethoxam	Neonicotinoid	Insecticide	Warning
Thiocyclam	Unclassified	Insecticide	Danger

Table 18. Characteristics of highly hazardous pesticides' active ingredients used by smallholder farmers for the management of arthropod pests in Kenya

Pesticide Active Ingredients	Chemical class	Use type	HHP1 Acute toxicity	HHP2 Carcinogenicity	HHP3 Mutagenicity	HHP4 Reproductive toxin	HHP5 POP	HHP6 PIC	HHP7 ODS
Abamectin	Fumigant	Nematicide	1	N	N	2	N	N	N
Beta-cyfluthrin			1B	N	N	2	N	N	N
Carbaryl	Carbamate	Insecticide	2	1B	N	N	N	N	N
Diazinon	Organophosphorous	Insecticide	2	1B	N	1B	N	N	N
Malathion	Organophosphorous	Insecticide, Acaricide	N	1B	N	N	N	N	N
Mancozeb	Dithiocarbamate	Fungicide, Oomycide	U	1B		2	N	N	N
Methomyl			1B	N	N	N	N	N	N
Propineb			U	1B	N	2	N	N	N

Farmers reporting challenges associated with whiteflies, *T. absoluta* and spider mites were, for their management, more likely to institute intervention measures (prior to consulting an extension agent) than would their counterparts experiencing challenges associated with cutworms and African bollworm. Finally, farmers in certain regions were more likely to institute intervention measures (prior to consulting an extension agent) for the management of arthropod pests than would their peers in other regions.

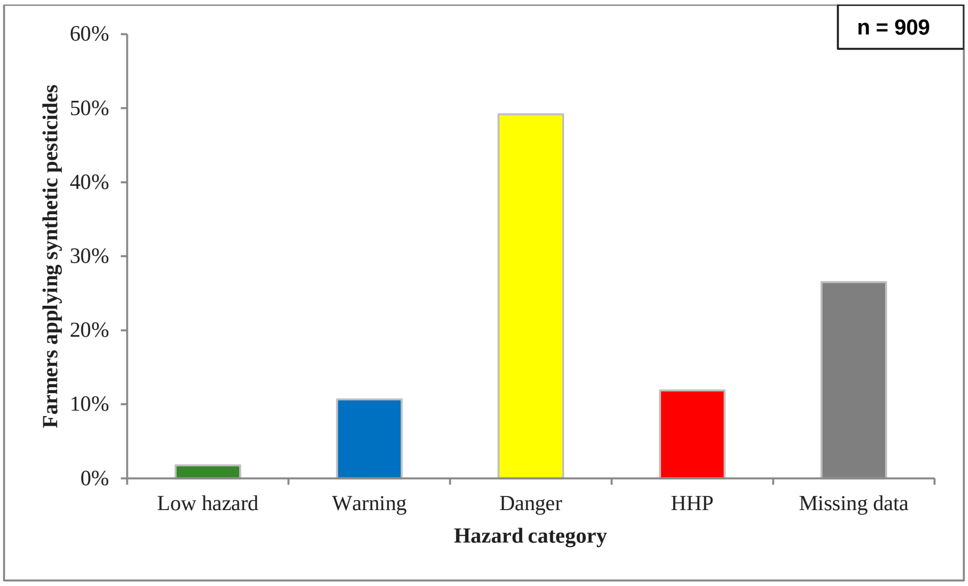


Figure 8. Farmers applying synthetic pesticides of different hazard categories

Table 19. Summary of results of Multinomial Logistic Regression for relationship between test variables and choice to intervene or not to intervene when it comes to management of arthropod pests

Test variables	Chi-Square	df	Sig.
Farmer region	16.905	6	**.010**
Farmer gender	.251	2	.882
Type of arthropod pest	230.981	18	**<.001**
Study year	47.669	6	**<.001**
Goodness-of-fit (analysis)	339.492	460	1.000

5.3.2 Influence of individual moderators on pest management practices prescribed by frontline agricultural extension officers

Nearly two-thirds of the recommendations were non-IPM practices. On the other hand, only a paltry 21 percent of the advice was IPM based while the remaining records, accounting for 18 percent, lacked an actual prescription (either left blank or no concrete management steps was prescribed). It is more likely that the type of recommendation prescribed by plant doctors was influenced by plant doctors' individual moderators namely gender, age, level of education and location (Table 20). An equal proportion (22%) of records prescribed by male and female plant doctors were IPM based (Figure 9a). However, there were gender disparities when it came to non-IPM based practices with seemingly a higher proportion of records submitted by male plant doctors (62%), relative to their female counterparts (58%), being non-IPM based.

Table 20. Summary of results of Pearson Chi-square test and Cramer's V statistic for relationship between test variables and pest management practices

Test variables	N	Pearson Chi-square test	df	Cramer's V test	Sig.
Age	3675	61.52	4	0.091	**<.001**
Edu. Level	3500	20.51	2	0.077	**<.001**
Gender	4064	13.18	2	0.057	**0.001**
Location	4538	77.22	6	0.092	**<.001**
Crop category	4619	74.31	10	0.090	**<.001**
Causative agent	4783	566.76	6	0.243	**<.001**

Also, compared to records submitted by male plant doctors, a higher proportion of records submitted by female plant doctors lacked an actual prescription or was left blank (Figure 9a). When it came to influence of plant doctors' age on prescribed pest management practice, there were more IPM-based records submitted by younger plant doctors than older ones (Figure 9b).

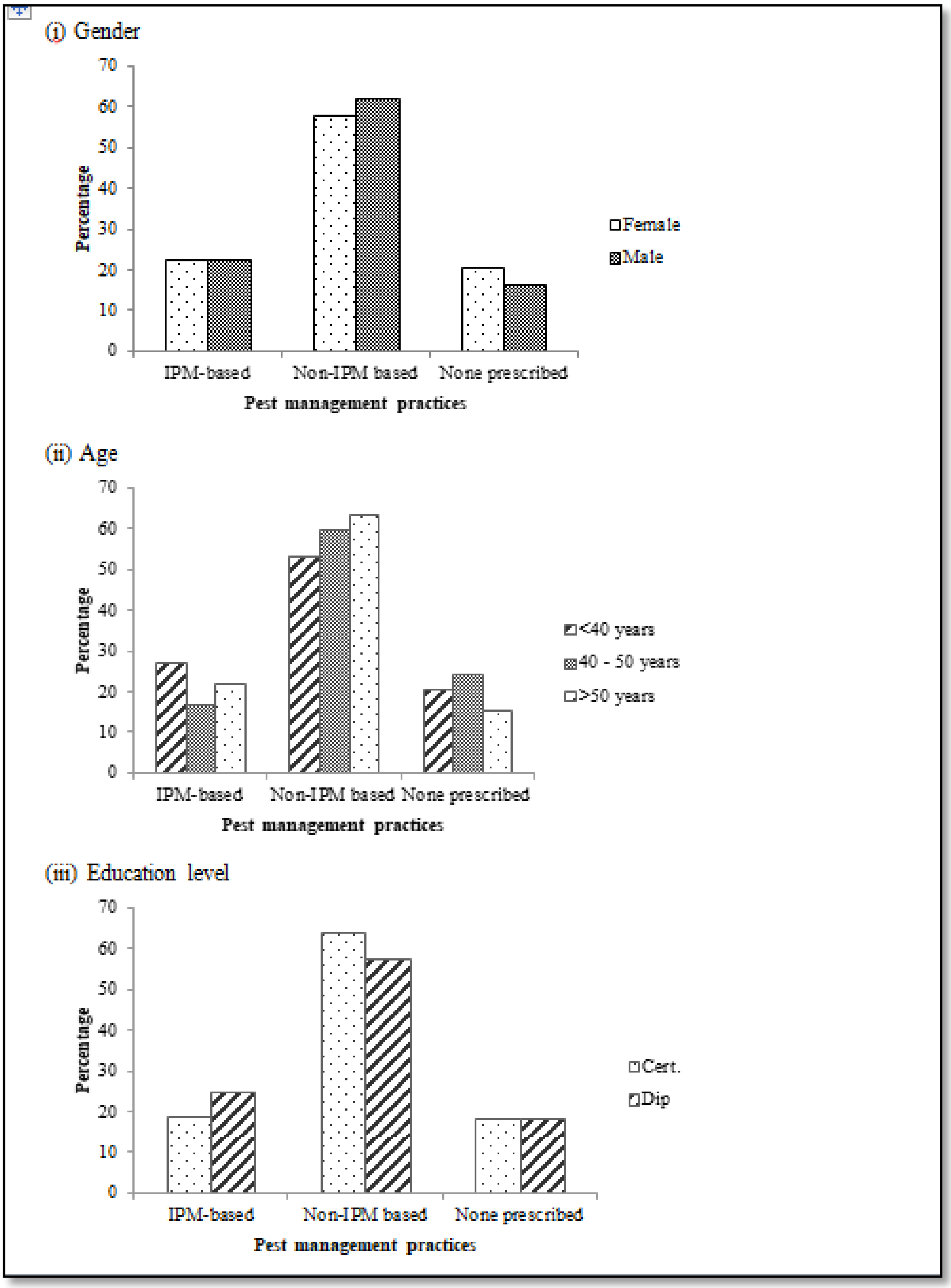


Figure 9: Percentage distribution of intervention measures based on extension officers' (a) gender, (b) age, and (c) education level

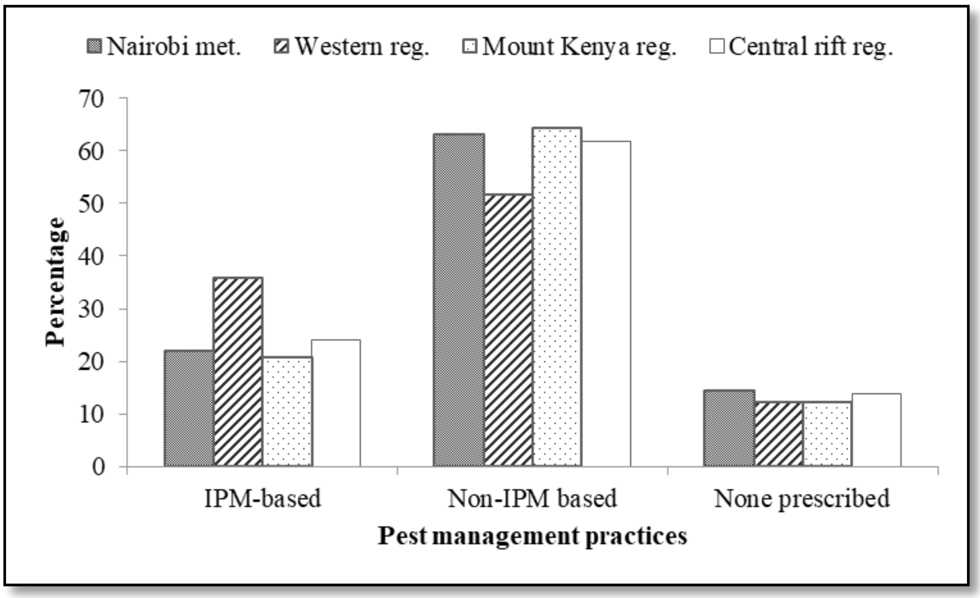


Figure 10: Percentage distribution of intervention measures based on extension officers' location

Similarly, more IPM-based records were submitted by plant doctors with higher education qualification (25%) than those of 'not-so-high' qualifications (18%) (Figure 9c). Finally, regional differences were also observed when it came to the number of IPM based records submitted by plant doctors in the different regions (Figure 10). In this category, Western region led in the number of IPM-based records (36%) while Mount Kenya region had the least (21%).

5.4 Discussion

5.4.1 Farmers' practices on management of arthropod pests of tomato

When it comes to the management of arthropod pests, a majority of the farmers opted not to intervene prior to consulting an agricultural extension officer. Perhaps, this was necessitated by the fact that; farmers often have limited or incomplete information about pest problems and possible management practices (Hashemi et al., 2009). Additionally, the findings may indicate that farmers in the study area place a great degree of trust in the agricultural extension system (Ochilo et al., 2018). This finding, however, contradicts previous studies that have questioned the technical competence of agricultural extension agents. According to Roberts (1989), the technical competence of agricultural extension agents is limited and in most instances is inferior to that of farmers who are technologically more advanced. The author further postulates that agricultural extension agents are recruited from "school failures" and are provided only with a superficial kind of technical training (Roberts, 1989). More recently, Krishnan and Patnam (2013) reported that extension as a model for promoting modern input adoption may not be very effective. Instead, the duo advocated for social learning as a preferred mechanism for the same on the account of its persistence nature (Krishnan and Patnam, 2013).

For farmers who attempted to control arthropod pests prior to consulting an agricultural extension agent, essentially, the use of synthetic pesticides was the preferred practice. According to De Bon et al. (2014), the desire for quick results obtained immediately following pesticide application is at the heart of farmers' preference for synthetic pesticides over other pest control methods. Coupled with this is the lack of proven alternatives and the sustained availability of moderately cheap pesticides which has ensured pesticides remain the focal pest management tactic (Talekar and Shelton, 1993, Ngowi et al., 2007). Another factor appearing to drive synthetic pesticide use is smallholder farmers' quest to increase yield or quality and deficiency of knowledge in how to attain this without reliance on synthetic pesticides (Williamson, 2003, De Bon et al., 2014). According to Ngowi et al. (2007), when it comes to the choice of pesticide to use, smallholders are highly influenced by vendors dealing in pesticides and who operate in their farming communities. Over time, however, trends in pesticides use by smallholder farmers is influenced by farmers' knowledge on pesticide application with respect to pests, weather conditions, price, farm size and efficacy of pest control products (Ngowi et al., 2007).

With 60% of the farmers applying synthetic pesticides using pest control products that are highly toxic, the risk of long-term effects of pesticides, if not properly handled, is high. The risk is especially pronounced where exposure to carcinogens and endocrine disruptors is involved (Ngowi et al., 2007). Endocrine disruptors manifest their deleterious effect through antagonizing or mimicking natural hormones in the body. The consequence of which, in the long-term, leads to human health effects including reproductive abnormalities, hormone disruption, cancer, diminished intelligence, and immunosuppression (Kesavachandran et al., 2009). According to Pedlowski et al. (2012), pesticide contamination can occur through direct and indirect means, and farmers and farm workers are perhaps the group at most risk by means of occupational exposure. High levels of occupational exposure to pesticides by this group could be explained by the group's supposedly low education impeding their ability to heed the hazard warnings provided by regulatory agencies. Other factors cited include lack of awareness regarding the dangers of pesticide misuse, the challenge of extrapolating the dosage from a large dimension-basis to very small areas, the absence of instructions in the pesticide label, the inability of applicators to understand the colour code system to enlighten them on the pesticide toxicity level, and lack of knowledge of pests (Pedlowski et al., 2012, De Bon et al., 2014). Furthermore, applicators who are conscious of the possible health hazards related to pesticides, and the advantages of personal protective equipment (PPE), do not always implement such measures. The main reasons provided for lack of use of PPE include discomfort of wearing PPE, cost, availability and general lethargy (Kesavachandran et al., 2009)

5.4.2 Influence of individual moderators on pest management practices prescribed by frontline agricultural extension officers

Much as IPM was prescribed to smallholder farmers, albeit on a limited scale, preferred pest management practice was the use of non-IPM technology. The small number of records prescribing IPM-based practices may be argued is the result of, among other things, the propagated notion that in instances of low productivity, the yield saved by IPM compared to 'doing nothing' may be too insignificant to warrant adoption. Based on this reasoning, IPM is viewed to be economically viable only under conditions of high productivity through which the cost of investment will be covered by increased revenue (Parsa et al., 2014). Another possible reason explaining the small number of IPM recommendations, as hypothesized by Parsa et al. (2014), is the belief that IPM requires collective action within a farming community. This belief is anchored on the premise that some pest management decisions are subservient to a collective action dilemma, thus returns from adopting a technology are dependent on whether others adopt it too. Finally, another possible reason explaining this phenomenon is the prominence, over the years, accorded to pesticide-based solutions (Sibanda et al., 2000, Parsa et al., 2014).

Notwithstanding the aforementioned, the choice of prescribed intervention differed significantly depending on the gender, age, education level and location of the prescribing plant doctor. The small number of records prescribing IPM-based practices by older plant doctors affirms the proposition that individuals with greater experience with existing technologies may be disposed to continue their dependence on existing technologies, and as such there may be a status quo bias (Sharma et al., 2011). Likewise, the finding of the study is in agreement with the commonly voiced premise that educated individuals are more likely to take up new technologies and/or are more likely to be early adopters (Nkamleu and Adesina, 2000).

Variations across regions in the management practices is probably to be expected considering the mix of cropping systems by location in Kenya, the network effects of the proportion of host crops in the region, and climatic differences varying pest pressures. Also, it may well be that in some regions the quality of crop being cultivated is such that it does not require or justify the use of certain management practices (Sharma et al., 2011).

Gender differences in the prescribed management practices could be an issue of attitude and compliance. It has been reported that women, more than men, are more likely to comply with instructions (Mazman et al., 2009). Through the activities of the technical experts, comprising the NDV team, Plantwise developed Pest Management Decision Guides (PMDGs) and factsheets (reference materials). These reference materials were shared with plant doctors as a practical guide on giving IPM biased recommendations, and it was expected plant doctors would refer to the guides as part of their routine plant clinic operations. Based on a traffic light system, PMDGs are comprehensive selections of the most appropriate preventative and curative management options for specific pest-crop combinations (Cameron et al., 2016). These information tools act as step-by-step guides for plant doctors to make recommendations for pest management beginning with preventative measures followed by proper pest monitoring before finally considering curative (direct control) measures. Of the direct control measures, priority is accorded to methods that can be applied without restrictions (e.g. no limit on frequency or timing of use) (Cameron et al., 2016).

5.4.3 Influence of crop type and type of causative agent on pest management practices prescribed by frontline agricultural extension officers

Compared to the other causative agents, it is not surprising that IPM-based practices were mostly prescribed for the management of plant diseases. This is because, the epidemiology of plant diseases, particularly the vectored ones, is complex and often, no single approach will achieve adequate control (Halbert, 2008). As it has been established, plant diseases result from a three-way interaction between the host, the pathogen and the environment (McNew, 1960, Lucas, 1998, Halbert, 2008). Seeing an epidemic ensues when all the components in the disease triangle are favourable to disease development, by manipulating one or more of these factors, one is able to render the conditions unsuitable for replication, survival or infection of the pathogen.

The high number of prescriptions forms recommending non-IPM based practices especially for the management of invertebrate pests confirms the assertion by Munyua et al. (2004) that in Kenya, non-IPM practices are given priority, and often recommended through extension as the main solution to pest problems. Probably this is because, non-IPM practices, particularly the exclusive use of synthetic pesticides, are perceived to work better than softer, less obtrusive materials. Additionally, they can be used to protect crops from anticipated pests, and used against active pest problems. However, there are ecological disruptions and safety problems associated with this high frequency of therapeutic use of synthetic pesticides. The four major problems encountered are pest resistance, pest resurgence, secondary pests and toxic residues (Lewis et al., 1997).

The results indicating the use of non-IPM practices was the most prescribed form of pest management among the crop groups is consistent with previous findings. Traditionally, farmers have been keen on using non-IPM practices, particularly the exclusive use of synthetic pesticides especially on vegetable crops with one study indicating that 3 out of 10 farmers in Kenya applied pesticide sprays once or twice per season, and another 43% sprayed pesticides more than three times in a season (Munyua et al., 2004).

Seeing the similarities between the options prescribed by ‘plant doctors’ in this study and the pest management practices adopted by farmers in Munyua et al. (2004) study lends credence to the notion that agricultural extension officers have immense influence on farmers.

5.5 Conclusion

In general, innovations are perceived to be more risky than traditional practices and this notion has received considerable support in literature. At the onset of an innovation, its potential users are usually uncertain of its effectiveness and tend to view its use as experimental. However, that uncertainty declines with learning, therefore inspiring more risk-averse users to adopt an innovation provided it is profitable. In this regard, to raise awareness among extension workers on ecological and economical sound approaches to management of crop pests, there is need for further investments in capacity building initiatives on IPM-based practices. This is essential in strengthening key technical and functional competencies required to drive effective selection and use of management tactics, based on cost/benefit analyses. In addition to the aforementioned initiatives, there is need to also encourage a knowledge transfer program that draws heavily on the expertise of frontline extension workers already prescribing ecological approaches to management of biotic and abiotic stressors. Indeed, communication of information and knowledge among peers is an essential facet of agricultural extension and advisory services, and extension agents must be able to access a continuous stream of new, regionally appropriate information and innovation if they are to be of continuous benefit to farmers.

For stakeholders in the plant health sector, the findings in this study indicate that a divide exists among the different segments of extension workers (based on gender, age, location and education level). Consequently, practitioners are better informed to formulate measures aimed at enhancing the adoption of technology among the various groups of extension workers. For example, IPM training programs for extension workers should be designed in ways that take cognizance of individual factors (gender, age, and education level) and contextual factors (crop types, causative agents and location). In formulating measures aimed at enhancing the adoption of ecological and economical sound approaches to management of biotic and abiotic stressors, practitioners should not restrict themselves only to IPM. Instead, as the study has highlighted, there is also need to build the capacity of extension officers on management of abiotic stressors. This is because abiotic causes also hamper crop production in the smallholder agricultural subsector of Kenya.

CHAPTER 6

DEVELOPMENT OF A BINOMIAL SEQUENTIAL SAMPLING PLAN FOR AN ARTHROPOD PEST OF TOMATO

6.1 Introduction

Arthropod pests severely constrain tomato production in the tropics. Among the major arthropod pests of tomato, *Solanum lycopersicum*, is the spider mite complex, *Tetranychus* spp., comprising *Tetranychus evansi* Baker and Pritchard and *Tetranychus urticae* Koch (Srinivasan, 2010, Azandémè-Hounmalon et al., 2014, Oduor, 2016, Zekeya et al., 2017). Spider mites are highly polyphagous and have been reported in various host plant species (Zhang, 2003, Agut et al., 2018). Their high reproductive potential coupled with their rapid development results in the fast population increase (Migeon et al., 2009, Boubou et al., 2011).

Control of spider mites has traditionally depended on acaricide treatments (Zhang, 2003, Saei Dehghan et al., 2009, Toroitich et al., 2014, OECD, 2016, Agut et al., 2018). However, the rapid development of resistance by mites, and new international trends favouring conservation and sustainable development of biological resources have all supported the use of IPM as opposed to the exclusive use of acaricides (Bueno et al., 2006, Provost et al., 2006, Perdikis et al., 2008)..

The foremost step in the development of any effective pest control strategy is the design of a sampling programme that factors sampling cost and resources (Shepard, 1980, Severtson et al., 2016). A farmer must be able to decide whether pests are present in sufficient numbers to warrant specific intervention (e.g. pesticide application). Presently, the lack of user-friendly, cost-effective sampling plans for arthropod pests, particularly among food crops, is a vital constraint to the adoption of IPM (Carvalho, 2016, Severtson et al., 2016, Lima et al., 2017, de Macêdo et al., 2019). Indeed, numerous studies have shown that deployment of practically feasible and reliable sampling plans could lead to a cutback in pesticide applications and enhanced pest management (Severtson et al., 2016). In developing a sampling plan, the procedure for sampling, a sampling unit, and a sampling design must all be defined. In addition, efficiency and accuracy, all of which are often competing needs, must be addressed (Pedigo and Buntin, 1993, Severtson et al., 2016). Furthermore, it is crucial that sufficient number of samples are obtained over a vast area to ensure that the data obtained is representative of the entire population. Upon making a valid estimate of the population density, an “action threshold” is applied in making a decision on whether an intervention is necessary or not (Carvalho, 2016, Severtson et al., 2016). An action threshold is defined as the least number of pests (intensity or density) or percentage of plants infested that will result in economic damage and as such should precipitate management action (Pedigo and Buntin, 1993).

A challenge to practical application of an action threshold for spider mites, particularly *T. evansi*, in tomato is that no sampling technique has been devised in which sampling effort has been confirmed by use of broad-scale empirical data. Consequently, field scouts, while sampling, are spending a lot of time, and even with that, they may not be able to accurately estimate *T. evansi* density in tomato fields. Both of these, represent major constraints to long-term sustainability of pest management. Development of both accurate and practically feasible sampling plans is thus crucial, and can be attained through modification and combination of stratified and conventional means to sampling plan development (Pedigo and Buntin, 1993, McGraw and Koppenhöfer, 2009, Butler and Trumble, 2012, Severtson et al., 2016, de Macêdo et al., 2019, Sequeira and Reid, 2019).

In this study, it is proposed that sequential sampling can be used to increase accuracy, and reduce the labour and time needed to scout tomato for *T. evansi*. This will in turn increase the chance for targeted acaricide applications in both time and space, ensuring application only when and where needed. Towards this, the following are determined: an appropriate sampling unit; the association between the proportion of infested sampling units and *T. evansi* densities (useful for development of a binomial sequential plan; and proposed stratified sampling mechanism on tomato fields (estimation of population density).

6.2 Materials and methods

Study area

The study was carried out at Ladybird Farm, Dudutech IPM Solutions in Naivasha, Nakuru County during 2 growing seasons of 2015: January – April (season 1) and May – September (season 2). The trial was set out in a well secured high tunnel. The units were kept devoid of pesticide contamination and were surrounded by a fine insect proof net that ensured the provision of adequate natural light as well as good ventilation.

Spider mite

Initiation of the spider mite colony was done in a rearing unit at Dudutech IPM solutions using mites collected from tomato, *Solanum lycopersicum*. At the start of the experiments, the mite colonies were maintained indoors for two weeks at 26^0c ± 10^0c and at 65 – 85% relative humidity.

Tomato cultivars

The tomato cultivars used as host plants consisted of three commercial varieties available in Kenya (Ann F1 - V1, Tylka F1 - V2, and Rio-Grande - V3). These cultivars were chosen on account of being most representative of cultivars cultivated in the country. In addition, 2 of the cultivars (Anna F1 and Tylka) were indeterminate hybrid bred. Tomato plants were raised on seedling trays before being transplanted at the cotyledon stage. The transplants were placed in a high tunnel maintained at 24^0C ± 10^0C and 50 – 85% relative humidity and on a 12/12-h light/dark regimen.

6.2.1 Within-plant distribution of *T. evansi*

Experiments were carried out in sandy to loam soil (topsoil was mostly sandy with poor water retention capacity). The growing spaces in the tunnels were divided into four 20 x 1m raised beds, manually made along its axis (Figure 11A/B). Within a bed, three $5m^2$ (5 x 1m) plots were established. Fresh market tomato seedlings were sown per hole at a depth of 0.5cm and thinned 2-3 days to maintain a tomato plant population within each plot at 16 plants (Figure 11C/D). After that, tree poles were erected about 5cm away from each tomato hill for support

(Figure 11E/F). The plants were then inoculated (2 weeks after transplanting) with *Tetranychus evansi*. During the growing season, water was applied through drip-irrigation in amounts sufficient to replenish evapotranspirative losses. Crop evapotranspirative was estimated on a weekly basis using data availed by a local weather station.

Preplant of broadcast double super phosphate (DSP) fertilizer was applied one teaspoonful per point. When plants attained a height of 25cm, they were top dressed, applying 16 kg of calcium ammonium nitrate (CAN) per 0.4 acres then 64 kg 4 weeks later. Plots were essentially kept weed-free by hand-weeding.

The vertical distribution of *T. evansi* on tomato leaves was determined using a destructive sampling technique. Also, for purposes of this study, the host plants were maintained in a one-stem system. Data was collected for six weeks following inoculation with *T. evansi*. During data collection, leaflets per plant were segregated into: young leaflets (YL) (partly uncurled and positioned at the end of branches); young-fully-opened leaflets (YFL) (fully uncurled and positioned beneath the young leaflets along branches); mature leaflets (ML) (fully uncurled and positioned beneath the YFL along branches). Eight plants were then randomly selected from each plot, and 4 leaflets randomly plucked from each of the three levels per plant.

Mite counts were then made following the procedure prescribed by Premachandra et al., (2005). Following the procedure, the tomato leaflets plucked from the plants were washed 3 times for ≈ 10s inside a plastic box (15 x 9 cm) filled with 250ml of 70% ethanol. Afterwards, the solution containing *T. evansi* was poured into a conical flask (200ml), shaken, and kept for a few minutes to allow the mites to settle. Following the settling of the mites inside the conical flask, the supernatant was decanted gently to 50ml. The suspension remaining inside the conical flask was then discharged onto a plate and counts made under a stereomicroscope. Counts of *T. evansi* were presented as mean ± standard error of the mean (SEM). Levene's test of equality of variance (Levene, 1960) was used to test the assumption of homogeneity of variance, and where there was a violation of the same, a modified version of ANOVA, Welch ANOVA, was used to analyse differences among the group means while Games-Howell post hoc test (Games and Howell, 1976) was used to compare all possible combinations of group means.

6.2.2 Development of binomial sequential sampling plan

Experiments were carried out in sandy to loam soil (topsoil was mostly sandy with poor water retention capacity). The growing spaces in the tunnels were divided into four 80 x 2m raised beds, manually made along its long axis. Within a bed, two 40m^2 (40 x 1m) blocks were established. Each block was further divided into twelve 2m^2 (2 x 1 m) plots. There was a single row per plot with 1m between plots and 50cm between plants. Seedlings were sown per hole at a depth of 0.5cm and thinned 2-3 days to maintain a tomato plant population within each plot at 6 plants. After that, tree poles were erected about 5cm away from each tomato hill for support. The plants were then inoculated with *T. evansi*

Two weeks after planting, the plants were inoculated with *T. evansi.* Half of the blocks were inoculated with a population comprising 30 mites and the other half with 130 mites each. The procedure followed in inoculating the mites entailed moving the prescribed number of *T. evansi* onto tomato leaf discs from the mother culture. The process of inoculating the tomato plants involved placing a mite-infested leaf disc at the centre of each plant.

Ninety-six plants from 6 blocks (48 inoculated with 30 mites and the other 48 inoculated with 130 mites) were destructively sampled each fortnightly. Counts of mites (except eggs) found on a single leaflet in each of the three strata were made following the procedure previously described. Counts of *T. evansi* were then made and data presented as mean ± standard error of the mean (SEM).

The following steps were employed in the advancement of a sequential sampling plan. Firstly, construction of the binomial sequential plan required calculation of mean (m), variance (S^2), and (proportion of units infested (PI). Taylor's power law was used to establish the relationship between mean and variance of *T. evansi* on YFL. The choice to study this association only on YFL, as opposed to all leaflets in the tomato plants was informed by the results presented in the previous section. Taylor's power law is described by the following equation: $S^2 = am^b$

> Where S^2 = variance, m = mean, and "a" and "b" are coefficients: "a" = a factor for sampling while "b" = an aggregation index (Taylor, 1961).

A linear regression was run to establish the influence of *T. evansi* mean on variance, and to assess linearity, a scatterplot of variance against *T. evansi* mean with a superimposed regression line was plotted. To establish if the linear regression model was a good fit, the percentage of variance explained was calculated by the researchers followed by calculation of statistical significance of the model using ANOVA.

Wilson et al. (1983) developed a binomial model which is represented in Equation 1. The model indicates the link between the average number (m) of pests per sampling unit and the proportion of sampling units infested by pests (PI). The model uses the association between mean and variance derived from Taylor’s equation (Taylor, 1961).

$$PI = 1 - e^{-\left(m\, ln\left(am\hat{}(b-1)\right)/\left(am\hat{}(b-1)-1\right)\right)} \quad [1]$$

Where “e” represents 2.72, the base Napierian logarithm (Ayoub, 1993).

Equation 1can be simplified and expressed as follows (Alatawi et al., 2005):

$$ln(1 - PI) = -m\, ln\,(am^{b-1})/(am^{b-1} - 1) \;\; [2]$$

Secondly, using data generated from the study, the fitness of the presence-absence model was assessed through regression analysis where the left and right-hand sides of equation 2 were matched against each other (Opit et al., 2003, Alatawi et al., 2005). Curvilinear regression was performed using SPSS Statistics procedure. Tally thresholds of 5, 10 and 20 mites per leaflet were evaluated to establish which of the three tally thresholds would result in the best fit.

Finally, the boundary lines were determined for three action thresholds (AT) using Cochran's Q test (Cochran, 1950). These action thresholds (0.1, 0.2 and 0.3 proportions) were selected based on proposals by practitioners (Severtson et al., 2016). Parameters for development of boundary lines (upper and lower) for all action thresholds were the same: $\alpha = \beta = 0.05$.

The decision boundaries (lower and upper) were calculated using the equations 3,4 (Wald, 1973):

$$Y = bn + h_0 \; [3]$$

$$Y = bn + h_1 [4]$$

The y-intercepts for the lower (h_0) and upper (h_1) decision boundaries were calculated as follows:

$$h_0 = \frac{ln[\beta/(1-\alpha)]}{ln\left[\frac{\theta_1(1-\theta_0)}{\theta_0(1-\theta_1)}\right]} \, [5]$$

$$h_1 = \frac{ln[(1-\beta)/\alpha]}{ln\left[\frac{\theta_1(1-\theta_0)}{\theta_0(1-\theta_1)}\right]} \text{ [6]}$$

Where θ_0 and θ_1 represent the lower and upper bounds of the AT, respectively. The common slope for the two sequential sampling boundary lines, λ, was obtained from Taylor's parameters, established from leaf infestation data.

Figure 11: High tunnel layout: (A, B) Growing spaces; (C, D) Transplanting of tomato seedlings; (E, F) Poles erected to support growing plants

6.2.3 Estimation of population density

Estimation of *T. evansi* populations on a plant area base was determined using a generalized formula of the model presented in equation 7 (Wilson et al., 1982, Wilson et al., 1983).

$$Mite\ density/m^2 = m_s \beta^{-1} \gamma^{-1} \rho \lambda^{-1} \text{ [7]}$$

Where m_s is the projected density of *T. evansi* per sampled YFL, β is the number of *T. evansi* on the sampled YFL as a fraction of the entire number on YFL, γ is the number of *T. evansi* on the YFL as a percentage of the entire number on all leaflets, ρ is the number of plants per meter-row, and λ is the spacing between rows (i.e. number of rows per meter).

For the study, only YFLs per plant were randomly selected for inspection whenever sampling was due. Since the number of YFL increased with time, β changed with time. Sampling for *T. evansi* was undertaken fortnightly. As a consequence, it became necessary to calculate β for each fortnight period of tomato production, meaning four values of β were calculated, one for each fortnight period during which destructive sampling was undertaken.

6.3 Results

6.3.1 Within-plant distribution of *T. evansi*

Population densities of *T. evansi* observed in the canopy strata exhibited differences with YFL having the highest population of red spider mites per leaflet ($n = 118, M = 134.55, SEM = 11.3$) followed by ML ($n = 158, M = 90.9, SEM = 8.1$). On the other hand, YL had the least population of red spider mites per leaflet ($n = 65, M = 61.9, SEM = 10.7$). Assessing the data using Levene's test for equality of variance showed that the assumption of homogeneity of variances was violated ($p < 0.05$). There were significant differences in *T. evansi* population among the different canopy strata, Welch's $F(2, 180.143) = 10.971, p < .0005$. Games-Howell post hoc analysis showed that the increase in *T. evansi* population from ML to YFL $\left(43.665, 95\%\ CI(10.87\ to\ 76.46)\right)$, and the decrease in *T. evansi* population from YFL to YL $\left(-72.643, 95\%\ CI(-109.44\ to - 35.84)\right)$ were statistically significant ($p = .005$ and $< .0005$, respectively).

There were significant differences in *T. evansi* population on different sampling days, Welch's $F(4, 162.808) = 13.585, p < .0005$. *Tetranychus evansi* population increased from day 7 (77.17 ± 9.84) to day 21 (84.22 ± 12.18), day 35 (115.97 ± 15.93), day 49 (159.09 ± 14.62), in that order. Putting tomato canopy strata in perspective, at the onset of sampling (7 days post-inoculation), the concentration of spider mites was evenly distributed between ML and YFL (Figure 12). However, in the subsequent sampling days, YFL had the most consistent and highest proportion of the entire spider mite population. Also, upon carrying out regression analysis for the average number of *T. evansi* on YFL against the entire number of *T. evansi* on each plant for each of the 4 sampling dates, there was a significant linear relationship (Table 21). Consequently, YFL appears as the most ideal part of the tomato plant to sample in order to assess *T. evansi* population.

A three-way ANOVA was carried out to assess the influence of sampling time, variety and the initial inoculation rate (high or low) on the population of *T. evansi* per leaflet. There was no statistically significant three-way interaction between sampling time, variety and the initial inoculation rate (high or low), $F(6, 315) = .248, p = .96$. Likewise, none of the two-way interactions explored were significant ($p < 0.05$).

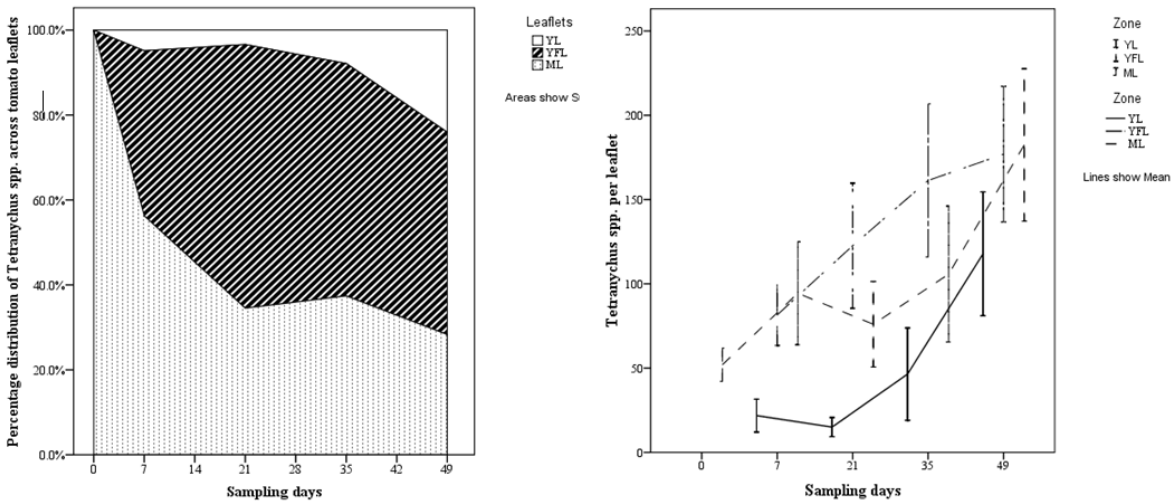


Figure 12: Patterns of within-plant distribution of *T. evansi* in the tomato canopy strata throughout the growing season

Table 21: Regression equations for forecasting the number of *T. evansi* on a tomato plant by use of mean number of *T. evansi* on YFL stratum for plants of ages 3 to 9 weeks

Days post-inoculation	Intercept ± SE	Slope ± SE	Slope P value	R^2
7	163.54 ± 101.9	1.56 ± 0.25	<0.001	0.465
21	440.44 ± 181.7	1.85 ± 0.26	<0.001	0.532
35	2448.04 ± 940.5	1.36 ± 0.23	<0.001	0.438
49	8081.67 ± 2954.9	1.38 ± 0.25	<0.001	0.39

6.3.2 Development of binomial sequential sampling plan

Visual inspection of a scatterplot of variance against *T. evansi* mean showed a linear relationship between the variables (Figure 13). Also, there was normality and homoscedasticity of the residuals. The prediction equation for the association between the average number of *T. evansi* per YFL and the variance (Equation 8), as projected by Taylor's power law, was statistically significant, $F(1, 216) = 213.552, p < .0005$ and accounted for 49.7% of the variation in variance with adjusted $R^2 = 49.5\%$ - which is a large size effect (Cohen, 1988)

$$\ln S^2 = 1.033 + 1.493 \ln m \ \ (R^2 = 0.497) \ [8]$$

On account of the high coefficient of determination (R^2 = 0.497), Taylor's power law effectively details the distribution of *T. evansi* on YFL. In addition, the slope was >1. By implication this means that *T. evansi* populations enjoy an aggregated distribution.

Since the mean-variance association of *T. evansi* was expressed by Taylor's power law, the model was utilized to describe the distribution of *T. evansi* on tomato, and using values derived from the study (a = 1.033; b = 1.493).

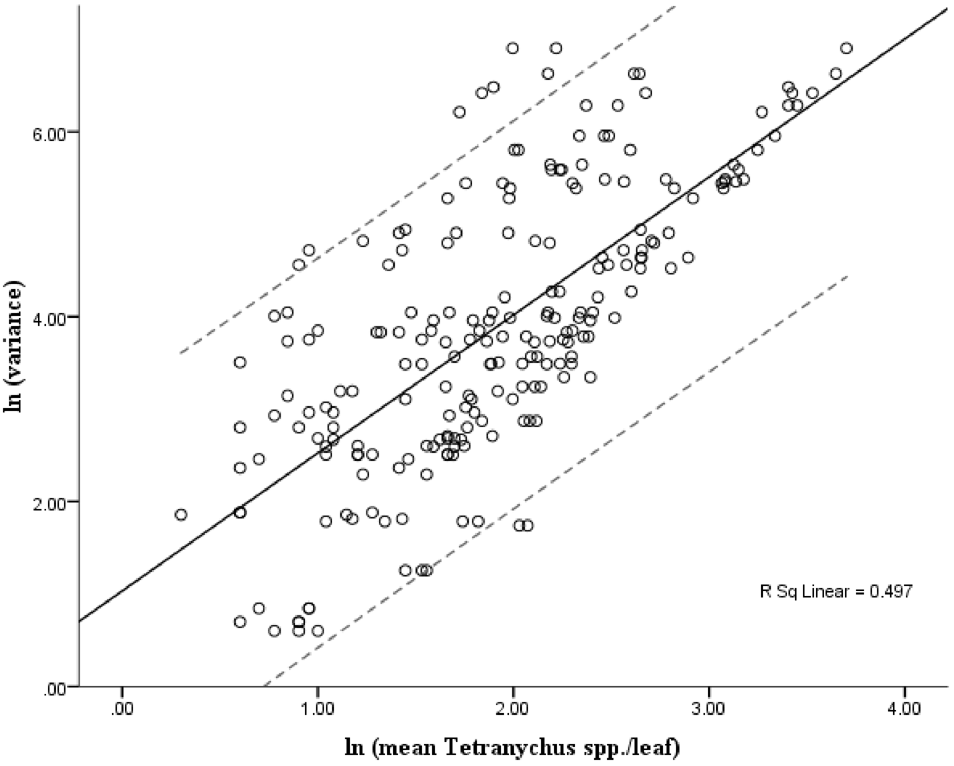


Figure 13: Association between the mean number of *T. evansi* and the variance on tomato leaflets

Assessing the fitness of the binomial model through regression analysis, where the left and right-hand sides of equation 2 were compared against each other, there was a statistically significant association between the two sides, and for all the three tally thresholds (Table 22). Because the tally threshold of 5 produced the highest R^2 value, 5 was selected as the preferred tally threshold for *T. evansi*.

Table 22: Regression equations showing fitness of binomial model at different tally threshold

Tally threshold	Intercept ± SE	Slope ± SE	Slope P value	R^2
5	3.77 ± 0.11	1.52 ± 0.32	<0.0005	0.153
10	3.85 ± 0.10	1.18 ± 0.30	<0.0005	0.149
20	3.92 ± 0.09	0.88 ± 0.28	<0.0005	0.141

Running Cochran's Q test (Cochran, 1950), the proportion of YFLs infested with *T. evansi*, at different time points, was found to be statistically significant, $\chi^2(3) = 38.458$, $p < .0005$. For the three AT of 0.1, 0.2, and 0.3, the binomial sequential sampling plans are shown in Figure

14. While sampling, if the aggregate sum of infested sampling units rises beyond the upper boundary line, the batch that has been sampled is regarded to be greater than the threshold, leading to a decision to treat. As well, if the aggregate sum of infested sampling units falls below the lower boundary line, the sampled batch is considered to be lower than the threshold, leading to a decision not to treat and to sample on another day

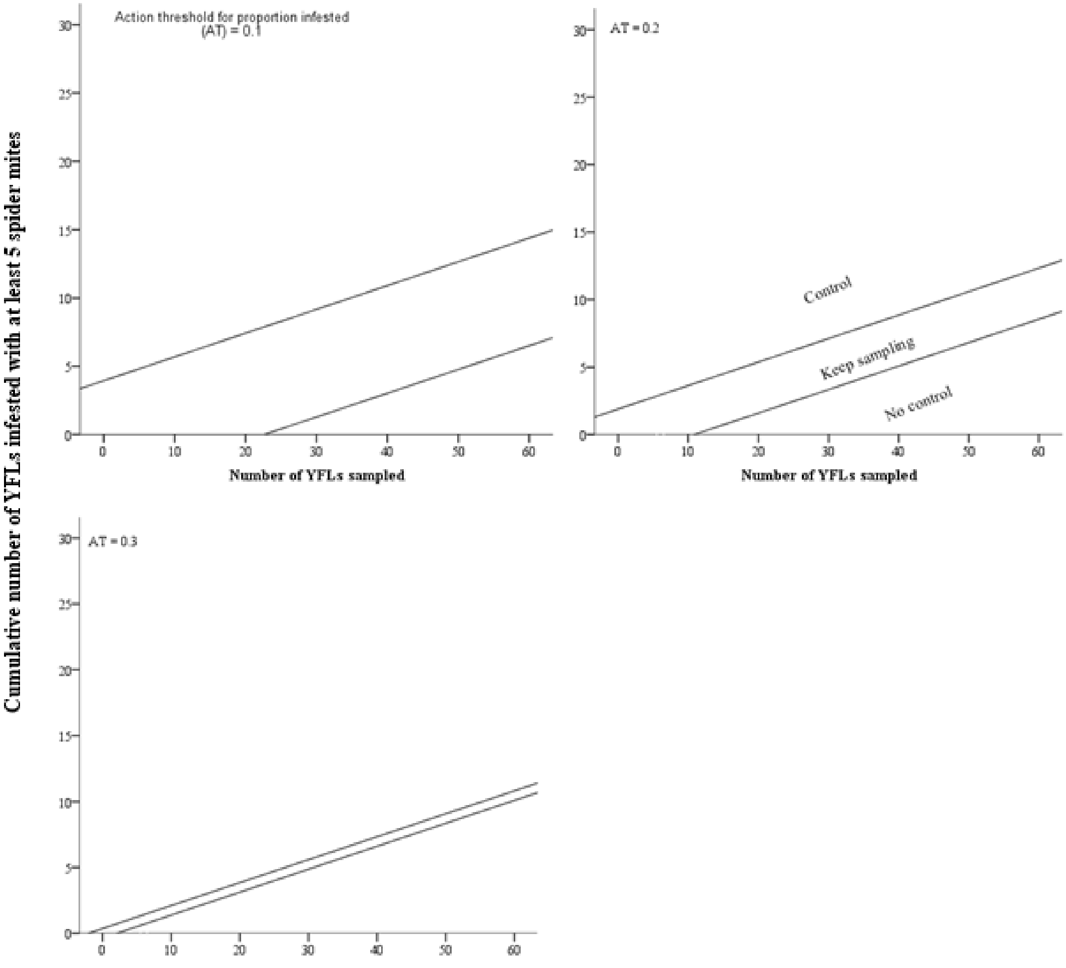


Figure 14: Decision boundary lines for the sequential sampling plan for spider mites on tomato based on three action thresholds (AT) of 0.1, 0.2, and 0.3 proportion of tomato infested with ≥ 20 spider mites and 0.05 α and β error parameters

6.3.3 Estimation of population density

In Table 23, the number of *T. evansi* on YFL sampled (as a fraction of the whole number on YFL) (β) and the number of *T. evansi* on the YFL (as a percentage of the entire number on all leaflets) (γ) for plants of ages 7 – 49 days after inoculation are computed. The values of β and γ for plants of ages 7 – 49 days after inoculation are needed for the determination of *T. evansi* population density per square meter. Looking at β, its value was significantly influenced by sampling date (F = 7.137; df = 3, 168; $P<0.001$). The type of variety, two-way interaction between season and time ((F = 1.112; df = 3, 168; P = 0.346) and three-way interaction between season, time and variety ((F = 0.144; df = 6, 168; P = 0.99) were not significant. The mean value of γ was 36%.

Table 23: Parameter estimates (±SEM) of β (the proportion of total *T. evansi* on all middle zones) and γ (proportion of total *T. evansi* on all middle zones) for 3 – 9 wk.-old plants

Days post inoculation	Mean β	Mean γ
7	0.514 ± 0.07	0.635 ± 0.21
21	0.539 ± 0.065	0.433 ± 0.153
35	0.359 ± 0.063	0.293 ± 0.117
49	0.201 ± 0.031	0.074 ± 0.013

6.4 Discussion

Choosing an appropriate sampling unit is critical when developing a sampling plan (Butler and Trumble, 2012). An analysis of within-plant distribution of *T. evansi* revealed that young-fully-opened leaflets (YFL) of ages 5 – 9 weeks sustained the apical and most steady proportion of the entire *T. evansi* population. Coupled with this, the YFL also held the highest mite density. Accordingly, non-destructive sampling plans designed for farmers should be anchored on counts of *T. evansi* in the YFL. Using the YFL as the sampling unit enhances efficiency and easiness of the sampling since the units to be sampled are comparable and readily recognized. Furthermore, the ability to detect *T. evansi* at depressed population densities is probable owing to the YFL being the most attacked.

The interaction between the location of the mite within the plant canopy and sampling date showed that the relative numbers of the mite in the three canopy strata changed over time. Immediately following inoculation, *T. evansi* was most abundant among the mature leaflets, but as the season progressed, the mites became abundant among the YFL, while their numbers progressively increased among the YL. This phenomenon could be attributed to the fact that *T. evansi* exhibits gregarious behaviour and only disperses to far-flung leaflets when its density is high and after the depletion of food reserves in the more established leaflets (Azandeme-Hounmalon et al., 2014, Azandéme-Hounmalon et al., 2015). According to Azandeme-Hounmalon et al. (2014), the dispersal mechanism of *T. evansi* make it possible for targeted control of the spider mite (by targeting the areas of aggregation, ‘high spots’) within the plant, particularly at the onset of an infestation.

In this study, Taylor’s regression model is used to assess the within-plant dispersion of *T. evansi* on tomato leaflets - not only showing an aggregated distribution, but also high coefficients of determination. These aggregation indices provide primary information for developing sampling programs geared at estimating population density (Cocco et al., 2015). For *T. evansi*, among the drivers for group-formation and living (aggregation) is the aspect of strengthened anti-predator functions (Dittmann and Schausberger, 2017, Gyuris et al., 2017). According to Dittmann and Schausberger (2017), anti-predator benefits of aggregation could arise from phenomena such as the dilution effect, encounter or avoidance effect, increased vigilance, cooperative defence, and predator confusion. The encounter or avoidance effect infers that an assemblage, though conspicuous, is often less likely noticed than individuals of the same group scattered over the same area. On the other hand, the dilution effect posits that the presence of alternative targets in a group reduces the predation risk of individual members of a group (Dittmann and Schausberger, 2017)

Binomial sampling is constructed around the relationship between the sample mean and the proportion infested - as established through use of suitable tally thresholds (TT) (Wilson and Room, 1983, Opit et al., 2003, Prager et al., 2013, Sequeira and Reid, 2019). In the present study, a tally threshold of 5 *T. evansi* per YFL provided a good description of the association between the mean of mites and the proportion of infested leaflets. By implication, this means, in instances where *T. evansi* population density is low, moderate or high using a TT of 5 should be sufficient (Sequeira and Reid, 2019).

The boundary lines provide for three decision choices for each AT and the cumulative number of YFLs (infested with at least 20 *T. evansi*) needed to decide being based on the AT for each sampling plan. For the 10% AT, sampling at least 23 YFLs will be required before arriving at a decision (lower bound intersection) (Figure 3). For the 20 and 30% ATs the minimum numbers of YFLs are 11 and 3, respectively (Figure 3). In instances where a pest control decision cannot be made (the cumulative number of infested sampling units indefinitely falls between the lower decision line and the upper line), sampling should be deferred to a later time. According to Cocco et al. (2015), the resampling period should be informed by the projected pest population growth, and when the crop is due for harvesting.

Timing of the sampling is important and it ought not to commence prior to the pest population becoming active or after the damage associated with the pest becoming unacceptable (Paula-Moraes et al., 2011). It would thus be convenient to link the binomial sequential sampling plan proposed in this study with other research, particularly on the degree-days required for *T. evansi* development.

The study further computes values of β (the number of *T. evansi* on sampled YFL as a percentage of the whole number on YFL) and γ (the number of *T. evansi* on the YFL as a percentage of the entire number on all leaflets) for tomato plants of ages 3 – 9 weeks. These values are crucial when it comes to calculating *T. evansi* density per square meter in tomato plant. Knowing both the density of *T. evansi* per square meter and the size of the area infested (expressed in square meters) enables the determination of the number of *T. evansi* in the concerned area which is established by multiplying these two parameters. Noteworthy, it has been reported that there are several factors in the production of crops that could impact the value of β. These factors include irrigation, fertilization, interspecific competition, heating (cooling), lighting and plant density (Denno et al., 1995, Altieri and Nicholls, 2003, Alatawi et al., 2005). In addition, according to Wilson et al. (1983), from a pest management perspective, the appropriate reliability of population estimates is established by variation between the pest management decision threshold and the population density, and this falls within the domain of sequential sampling. In instances where population density is above or below the threshold, a small number of sample units are needed to establish the population lies on which side of the threshold. On the other hand, as the population density nears the threshold, the number of samples needed is greater (Wilson et al., 1983).

6.5 Conclusion

Sequential sampling avails a mechanism for reducing and optimizing the sampling effort in instances where few samples are needed. Binomial sequential sampling, in particular, requires the slightest sampling effort since, unlike counting of pests on individual plants, evaluation of the presence or absence of a pest in a plant is less time-consuming. In the present study, an action threshold for *T. evansi* on tomato is premised on the proportion of tomato YFLs infested, instead of *T. evansi* counts. This bolsters the use of binomial data in the formulation of a sampling plan instead of data resulting from counts of an arthropod pest on individual plants. The binomial sequential sampling plan for *T. evansi* that has been developed in this study the potential to significantly reduce the effort and time needed in the effective management of this pest. Notwithstanding, since the sampling plans are based on ATs and not exhaustively researched economic thresholds, there is room for improvement. Future research detailing the relationship between yield-loss and *T. evansi* damage on tomato would avail more precise thresholds for sampling plan development. Also, important for practitioners to customize the sampling plans developed here by considering costs associated with pest management, an appropriate type I and II error rates, and best periods to truncate sampling in order to achieve the desired aims of the *T. evansi* management program.

CHAPTER 7
GENERAL DISCUSSION, CONCLUSION AND RECOMMENDATIONS

7.1 General discussion

7.1.1 What are the characteristics and production constraints of smallholder tomato production in Kenya?

There is male dominance and insufficient youth participation in tomato production in Kenya. These could be credited to factors including access to human and physical capital, access to land, and lack of viable markets and targeted extension support. All these factors, some of which male farmers also contend with, seem to affect the youth and female farmers more than older male farmers (Clottey et al., 2009, Chinsinga and Chasukwa, 2012, Bezu and Holden, 2014, Mwangi et al., 2015).

Over the recent past, there has been a decline in area under tomato cultivation in Kenya. Possibly, this could be the result of more farmers adopting high-yielding varieties which ensure increased production using less land. Alternatively, disaffection by farmers in the cultivation of tomato may be another possible reason (Odame et al., 2009, Geoffrey et al., 2014).

In terms of adoption of high-yielding varieties, there is limited adoption of the same by farmers. Most of the smallholder farmers seem to prefer the traditional varieties. Underlying this preference could be cost considerations (farmers preferring less expensive varieties), preference for determinate and processing tomato varieties. Finally, smallholder tomato production in Kenya is constrained by biotic and abiotic factors, including pests and diseases, with variations in incidences being observed based on location and over time

7.1.2 What is the influence of abiotic factors (agro-ecological zonation) and time on the distribution patterns of arthropod pests of tomato?

A diverse range of arthropod pests were found to hamper smallholder tomato production in Kenya. Despite variations in arthropod pests' frequency, *T. absoluta*, whiteflies and spider mites were the most reported pest species, confirming their major pest status on tomatoes as earlier reported by Oduor (2016) and Zekeya et al. (2017).

In terms of agro-ecological zonation, most of the arthropod pests reported were associated with upper and lower midland zones while only a few were reported in upper highland zones. Also, incidences of arthropod pests showed considerable inter-year differences. These phenomena could be credited to the fact that altered weather patterns increase or decrease crop vulnerability to pest infestations (Rosenzweig et al., 2001). With climate change in perspective, future consequences for the performance of arthropod pests will certainly depend on the degree and character of climate change in the various AEZs. Coupled with altered weather patterns, over time, migrant pests (such as *T. absoluta*) are colonizing new habitats.

7.1.3 What are farmers and extension agents' current practices for management of arthropod pests of tomato?

When it comes to the management of arthropod pests, a majority of farmers are opting not to intervene prior to consulting with an agricultural extension officer. Perhaps, this is necessitated by the fact that; farmers often have limited or incomplete information about pest problems and possible management practices (Hashemi et al., 2009). Also, it may well be that smallholder farmers still place a great degree of trust in the agricultural extension system (Ochilo et al., 2018). This finding, however, contradicts previous studies that have questioned the technical competence of agricultural extension agents or the continued usefulness of public agricultural advisory services.

For farmers who attempt to control arthropod pests prior to consulting pest management practitioners, the use of synthetic pesticides is the preferred practice. According to De Bon et al. (2014), the desire for quick results obtained immediately following pesticide application is at the heart of farmers' preference for synthetic pesticides over other pest control methods. Of the farmers applying synthetic pesticides, 60% of them use pest control products that are highly hazardous.

Much as IPM is being prescribed to smallholder farmers, albeit on a limited scale, preferred pest management practice by agricultural extension agents is the use of non-IPM technology. The small number of records prescribing IPM-based practices could be argued is the result of, among other things, the propagated notion that in instances of low productivity, the yield saved by IPM compared to 'doing nothing' may be too insignificant to warrant adoption. Based on this reasoning, IPM is viewed to be economically viable only under conditions of high productivity through which the cost of investment will be covered by increased revenue (Parsa et al., 2014).

The choice of prescribed intervention differs significantly depending on the gender, age, education level and location of the prescribing plant doctor. Individuals with greater experience with existing technologies appear disposed to continue their dependence on existing technologies, and as such there is a status quo bias. Educated individuals, on the other hand, appear more inclined to take up new technologies. Variations across regions in the management practices prescribed is probably the result of a multiplicity of factors including the network effects of the proportion of host crops in the region, and climatic differences varying pest pressures. Finally, gender differences in the prescribed management practices could be an issue of attitude and compliance.

7.1.4 Can adoption of binomial sequential sampling plan contribute to optimization of sampling intensity required for arthropod pest control decisions?

The binomial sequential sampling plan for *T. evansi* developed in this study has the potential to significantly reduce the effort and time needed for effective management of arthropod pest. Firstly, selection of an appropriate sampling unit (YFLs), as opposed to sampling the entire canopy strata, has enhanced efficiency and easiness of sampling.

Secondly, when sampling pests occurring in high densities, binomial sampling plans have the potential to significantly reduce sampling costs. This is because binomial sampling is constructed around the relationship between the sample mean and the proportion of sampling units infested - as established through use of suitable TTs. In the present study, a TT of 5 *T. evansi* per YFL provide a good description of the association between the mean of the mites and proportion of infested leaflets.

Finally, the boundary lines provide for three decision choices for each AT, and the cumulative number of YFLs (infested with at least 5 *T. evansi*) needed to decide being based on the AT for each sampling plan. For the 10% AT, sampling at least 23 YFLs will be required before arriving at a decision. For the 20 and 30% ATs the minimum numbers of YFLs are 11 and 3, respectively (Figure 14). In instances where a pest control decision cannot be made, sampling should be deferred to a later time.

7.2 Conclusion and recommendation

Through use of an integrated systems approach to innovation, the study has identified a number of constraints and opportunities in the quest to effective management of arthropod pests in the smallholder tomato production in Kenya. These constraints and opportunities are not only agronomic (crop protection) in nature, but cut-across varied fields and levels of integration, and involve multiple stakeholders.

For each of the constraints/opportunities identified in the study (e.g. farmers' over-reliance in highly hazardous synthetic pesticides, status quo bias among practitioners, lack of user-friendly, cost-effective sampling plans for arthropod pests etc.), there is need to (1) consider both the definitive as well as the broader context, and (2) rigorously evaluate whether the constraint/opportunity should be prioritised and how remedies suggested reverberate with interests and needs of various stakeholders. The process of unearthing this will require engagement of individuals from a broad, multidisciplinary backgrounds, who will in turn work closely with other stakeholders across all levels (crop, farm, community, region and country).

As identified in the study, any sustainable approach towards management of arthropod pests within the context of smallholder tomato production in Kenya should consider the following five verities:

(1) *Farmers' circumstances (resources and constraints)* – presently, there is male dominance and insufficient youth participation in tomato production in Kenya. In addition, area under tomato cultivation has been on the decline; there is minimal adoption of high-yielding varieties; and farmers, besides arthropod pests, also contend with other biotic and abiotic factors, including diseases and nutrient deficiencies – with variations in incidences being observed based on location and time.

(2) *The pest problem* - a diverse range of arthropod pests hamper smallholder tomato production in Kenya; key among them being *T. absoluta*, whiteflies and spider mites. Agro-ecological zonation and time have a significant influence on the distribution patterns of arthropod pests.

(3) *Decision-making by farmers and agricultural extension agents* – a substantial number of farmers opt not to intervene whenever they encounter arthropod pests' problems. For those compelled to act, there are those among them who first consult with practitioners in the plant health sector (mostly agricultural extension agents) before employing any

intervention, while the rest are inclined to intervene mostly through use of synthetic pesticides. Among extension agents, much as IPM is being prescribed to smallholder farmers, albeit on a limited scale, preferred pest management practice by agricultural extension agents is the use of non-IPM technology.

(4) *Pesticide use* – the present regime is defined by increasing use of pesticides, including highly hazardous pesticides. There is need, therefore, to reverse the situation and to bring pesticide use to 'acceptable' level. This may entail using pesticides in concomitance with other non-pesticide controls; promotion of effective yet less hazardous pesticides; promotion of safe and healthy practices relating to use, storage and disposal of pesticides; and rotation of various pesticides to avoid build-up of resistance.

(5) *Decision support tools* – opportunities exist both for research as well as for uptake of a wide range of tools (methods, techniques and/or simulation models) geared towards supporting participatory processes and decision analysis by farmers e.g. development and deployment of sequential sampling plans that enable farmers to decide whether pests are present in sufficient numbers to warrant specific intervention.

Evidently, systems approach for management of arthropod pests is bound to evolve as new technical and scientific advances come to the fore. National cropping systems are bound to change - propelled by economics and markets. New migrant pests are likely to colonize new habitats leading to the changes to the system and realignment of priorities. In light of the foregoing, it would be naïve to assume that all assumptions relating to anthropogenic and ecosystem effects should be cast in stone.

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APPENDICES

Appendix 1: Nutrient data for tomatoes

Nutrient	Unit	Value per 100g
Water	g	94.52
Energy	kcal	18
Protein	g	0.88
Total lipid (fat)	g	0.2
Carbohydrate, by difference	g	3.89
Fiber, total dietary	g	1.2
Sugars, total	g	2.63
Minerals		
Calcium, Ca	mg	10
Iron, Fe	mg	0.27
Magnesium, Mg	mg	11
Phosphorus, P	mg	24
Potassium, K	mg	237
Sodium, Na	mg	5
Zinc, Zn	mg	0.17
Vitamins		
Vitamin C, total ascorbic acid	mg	13.7
Thiamin	mg	0.037
Riboflavin	mg	0.019
Niacin	mg	0.594
Vitamin B-6	mg	0.08
Folate, DFE	µg	15
Vitamin B-12	µg	0
Vitamin A, RAE	µg	42
Vitamin A, IU	IU	833
Vitamin E (alpha-tocopherol)	mg	0.54
Vitamin D (D2 + D3)	µg	0
Vitamin D	IU	0
Vitamin K (phylloquinone)	µg	7.9
Lipids		
Fatty acids, total saturated	g	0.028
Fatty acids, total monounsaturated	g	0.031
Fatty acids, total polyunsaturated	g	0.083
Fatty acids, total trans	g	0
Cholesterol	mg	0
Amino Acids		
Other		
Caffeine	mg	0

Source: USDA National Nutrient Database for Standard Reference (USDA, 2018)

Appendix 2: Plant clinic locations

Location	Agro-ecological zones	Zone name	Latitude	Longitude
Bungoma				
Kimilili				
1. Chebukwabi Market	Upper Midland Zones (humid)	UM1	0.79611	34.66553
2. Kamukuywa	Upper Midland Zones (sub humid)	UM2	0.77862	34.78950
3. Kibisi	Upper Midland Zones (humid)	UM1		
4. Kibunde	Upper Midland Zones (sub humid)	UM2	0.73706	34.68772
5. Kimilili Market	Upper Midland Zones (sub humid)	UM2	0.77749	34.71794
6. Nasusi	Upper Midland Zones (humid)	UM1	0.81863	34.75862
7. Sikhendu	Upper Midland Zones (semi-humid)	UM3	0.77076	34.75954
8. Sinoko	Upper Midland Zones (semi-humid)	UM3		
Elgeyo Marakwet				
Marakwet West				
9. Chebubai			0.98482	35.45752
10. Cheptongei	Upper Highland Zones (humid)	UH1		
11. Chesubet	Lower Highland Zones (sub humid)	LH2	1.06012	35.28718
12. Kabanon Kapkamak	Lower Highland Zones (sub humid)	LH2	0.95475	35.61245
13. Kamoi	Lower Highland Zones (sub humid)	LH2		
14. Kapcherop	Upper Highland Zones (humid)	UH1	1.03927	35.32052
15. Kimnai	Upper Highland Zones (sub humid)	UH2	1.02969	35.45550
16. Kokwongoi	Upper Highland Zones (sub humid)	UH2	1.02074	35.43056
17. Makutano	Upper Highland Zones (sub humid)	UH2	-1.40847	37.48090
Embu				
Manyatta				
18. Embu Municipal Market	Upper Midland Zones (transitional)	UM4	-0.5365	37.45410
19. Kairuri	Upper Midland Zones (humid)	UM1		
20. Karingari	Upper Midland Zones (semi-humid)	UM3	-0.46959	37.50620
21. Kathangariri	Lower Highland Zones (humid)	LH1		
22. Kibugu	Upper Midland Zones (humid)	UM1	-0.44200	37.43680

Location	Agro-ecological zones	Zone name	Latitude	Longitude
23. Kithimu	Upper Midland Zones (transitional)	UM4	-0.51003	37.52088
24. Kithungururu			-0.41337	37.45690
25. Makathi	Upper Midland Zones (transitional)	UM4	-0.51128	37.47353
26. Manyatta	Upper Midland Zones (semi-humid)	UM3	-0.42613	37.47909
27. Mutunduri	Upper Midland Zones (sub humid)	UM2	-0.47389	37.46408
28. Rukira	Upper Midland Zones (semi-humid)	UM3	-0.48696	37.53921
Mbeere North				
29. Kathiga Gaceru	Lower Midland Zones (transitional)	LM4	-0.50537	37.72824
Runyenjes				
30. Kavutiri	Upper Midland Zones (sub humid)	UM2	-0.41880	37.50349
Kajiado				
31. Kajiado North				
32. Matasia	Upper Midland Zones (semi-humid)	UM3	-1.38932	36.68352
Kajiado West				
33. Kibiko	Upper Midland Zones (semi-humid)	UM3	-1.34418	36.64176
34. Kiserian	Upper Midland Zones (semi-humid)	UM3		
Oloitokitok				
35. Entarara	Lower Midland Zones (semi-arid)	LM5	-2.99827	37.62601
36. Kuku Township	Lower Midland Zones (arid)	LM6	-2.89405	37.58843
37. Namelok	Lower Midland Zones (semi-arid)	LM5	-2.71889	37.46388
38. Nguruman	Lower Midland Zones (arid)	LM6	-1.79007	36.05950
39. Njukini	Lower Midland Zones (transitional)	LM4		
40. Ololopon	Lower Midland Zones (semi-arid)	LM5	-2.92791	37.50887
41. Olorika	Lower Midland Zones (arid)	LM6		
Kiambu				
Kabete				
42. Karura	Upper Midland Zones (humid)	UM1	-1.20150	36.72549
43. Nyathuna	Lower Highland Zones (semi-humid)	LH3		
44. Wangige	Lower Highland Zones (semi-humid)	LH3	-1.21993	36.71340
Kikuyu				
45. Dagoreti	Upper Midland Zones (semi-humid)	UM3	-1.28308	36.72670
46. Gikambura	Upper Midland Zones (semi-humid)	UM3	-1.27974	36.64481

Location	Agro-ecological zones	Zone name	Latitude	Longitude
47. Kamangu	Upper Midland Zones (semi-humid)	UM3		
48. Lusengeti	Upper Midland Zones (semi-humid)	UM3	-1.28124	36.61225
49. Nderi	Upper Midland Zones (semi-humid)	UM3	-1.21822	36.65172
Limuru				
50. Ngecha	Lower Highland Zones (humid)	LH1	-1.16952	36.66641
Kirinyaga				
Mwea East				
51. Kutus	Lower Midland (semi-humid)	LM3	-0.57318	37.32643
52. Miuu	Lower Midland (semi-humid)	LM3	-0.60549	37.46312
53. South Ngariama	Upper Midland Zones (humid)	UM1		
54. Togonye	Upper Midland Zones (semi-humid)	UM3	-0.57659	37.43290
55. Wang'uru	Lower Midland Zones (transitional)	LM4	-0.68136	37.35478
Mwea West				
56. Kandongu	Lower Midland (semi-humid)	LM3	-0.66629	37.29370
57. Kimicha	Lower Midland (semi-humid)	LM3	-0.58570	37.29047
58. Marura	Lower Midland (semi-humid)	LM3	-0.64575	37.31893
59. Nyaga				
Machakos				
Kathiani				
60. Ithaeni	Lower Midland Zones (transitional)	LM4		
61. Kauti	Upper Midland Zones (arid)	UM6	-1.41250	37.33193
62. Kaveani	Lower Midland Zones (transitional)	LM4	-1.46785	37.30344
63. Mitamboni	Upper Midland Zones (transitional)	UM4	-1.37581	37.25049
Machakos				
64. Katoloni	Upper Midland Zones (transitional)	UM4	-1.58253	37.24501
65. Kola	Upper Midland Zones (arid)	UM6	-1.70561	37.34783
66. Machakos Municipal Market	Upper Midland Zones (semi-arid)	UM5	-1.52005	37.27124
67. Mumbuni	Upper Midland Zones (semi-arid)	UM5	-1.49538	37.26630
Mwala				
68. Kabaa	Lower Midland (semi-humid)	LM3	-1.23515	37.47248
69. Kamwala	Lower Midland (semi-humid)	LM3		

Location	Agro-ecological zones	Zone name	Latitude	Longitude
70. Kivandini	Lower Midland (semi-humid)	LM3	-1.32801	37.44187
71. Makutano	Lower Midland Zones (transitional)	LM4	-1.40847	37.48090
Nakuru				
Bahati				
72. Bahati	Upper Midland Zones (semi-humid)	UM3	-0.15368	36.14514
73. Dundori	Lower Highland Zones (transitional)	LH4	-0.25462	36.23458
74. Kabatini	Lower Highland Zones (semi-humid)	LH3	-0.21590	36.16480
75. Kagoto	Lower Highland Zones (transitional)	LH4	-0.25034	36.11021
76. Karunga	Upper Midland Zones (semi-humid)	UM3	-0.17645	36.16510
77. Kirima	Lower Highland Zones (transitional)	LH4	-0.15732	36.10500
78. Maili Tisa	Upper Midland Zones (semi-humid)	UM3	-0.18923	36.12451
Nakuru East				
79. Free Area	Lower Highland Zones (semi-humid)	LH3		
Subukia				
80. Baraka	Lower Highland Zones (semi-humid)	LH3	-0.10476	36.16259
81. Kabazi	Lower Highland Zones (sub humid)	LH2	-0.07661	36.16851
82. Kiboronjo	Lower Highland Zones (semi-humid)	LH3	-0.11530	36.22250
83. Kihoto	Lower Highland Zones (semi-arid)	LH5	-0.08210	36.18061
84. Lari Wendani	Lower Highland Zones (semi-arid)	LH5	0.12731	36.26622
85. Maombi	Lower Highland Zones (sub humid)	LH2		
86. Munanda	Lower Highland Zones (semi-arid)	LH5	-0.03581	36.19826
87. Subukia	Lower Highland Zones (semi-humid)	LH3	0.00295	36.22740
88. Tetu	Lower Highland Zones (semi-humid)	LH3	-0.03800	36.22201
Narok				
Narok North				
89. Mosiro	Lower Midland Zones (arid)	LM6	-1.45181	36.07036
90. Murwa			-0.97813	35.95142
91. Olkeri	Upper Midland Zones (semi-arid)	UM5	-0.85485	35.66429
92. Olopito	Lower Highland Zones (semi-humid)	LH3	-0.96993	35.89854
93. Rotian	Lower Highland Zones (semi-humid)	LH3		
94. Siyapei	Lower Highland Zones (semi-humid)	LH3		

Location	Agro-ecological zones	Zone name	Latitude	Longitude
Narok South				
95. Enosogon	Lower Highland Zones (sub humid)	LH2		
96. Sogamu	Lower Highland Zones (sub humid)	LH2	-1.08946	35.95505
97. Timkaitit	Lower Highland Zones (sub humid)	LH2	-0.82675	35.67067
Nyeri				
Mukurweini				
98. Gakindu	Upper Midland Zones (semi-humid)	UM3	-0.56745	36.99700
99. Giathugu	Upper Midland Zones (semi-humid)	UM3	-0.55890	37.07500
100.Gikondi	Upper Midland Zones (semi-humid)	UM3	-0.57714	37.03649
101.Ichamara	Upper Midland Zones (semi-humid)	UM3	-0.54507	37.08178
102.Kaharo	Upper Midland Zones (semi-humid)	UM3		
103.Kaheti	Upper Midland Zones (semi-humid)	UM3	-0.53427	37.05557
104.Karaba	Upper Midland Zones (semi-humid)	UM3	-0.62768	37.10609
105.Maganjo	Upper Midland Zones (semi-humid)	UM3		
Siaya				
Alego Usonga				
106.Boro	Lower Midland Zones (sub humid)	LM2	0.08633	34.23424
107.Uranga Usonga	Lower Midland Zones (sub humid)	LM2	0.06041	34.28298
Ugunja				
108.Ugunja	Lower Midland Zones (sub humid)	LM2	0.19073	34.29595
Tharaka Nithi				
Chuka Igambang'ombe				
109.Kajuki	Lower Midland Zones (transitional)	LM4	-0.33561	37.82998
110.Kamaindi	Lower Midland Zones (semi-arid)	LM5	-0.38153	37.83992
111.Kiang'ondu	Lower Midland Zones (transitional)	LM4	-0.32219	37.62248
112.Makanyanga	Lower Midland Zones (semi-arid)	LM5		
113.Mbogoni	Lower Midland Zones (transitional)	LM4	-0.41188	37.68892
114.Mugirirwa	Lower Midland Zones (transitional)	LM4		
115.Muiru	Lower Midland Zones (semi-arid)	LM5	-0.35426	37.66642
116.Ndagani	Lower Midland Zones (transitional)	LM4	-0.31859	37.65946
117.Rukindo	Lower Midland Zones (semi-arid)	LM5		
Trans Nzoia				
Kwanza				

Location	Agro-ecological zones	Zone name	Latitude	Longitude
118.Kesogon	Lower Highland Zones (sub humid)	LH2	1.16485	35.11218
119.Kimase	Lower Highland Zones (semi-humid)	LH3		
120.Kimondo	Lower Highland Zones (semi-humid)	LH3		
121.Kwanza	Lower Highland Zones (semi-humid)	LH3	1.16267	35.00110
122.Maili Saba	Upper Midland Zones (transitional)	UM4	1.09328	35.07555
123.Matumbei	Lower Highland Zones (semi-humid)	LH3	1.09704	34.78779
Trans Nzoia East				
124.Geta	Lower Highland Zones (sub humid)	LH2	1.02563	35.27245
125.Kachibora	Upper Midland Zones (transitional)	UM4	0.98222	35.22098
126.Kapsara	Upper Midland Zones (transitional)	UM4	1.08972	35.15419
127.Sibanga	Upper Midland Zones (transitional)	UM4	1.02874	35.12113
128.Tugoini	Upper Midland Zones (transitional)	UM4	0.93466	35.27615
129.Trans Nzoia West				
130.Gituamba	Lower Highland Zones (sub humid)	LH2	0.93371	34.76890
131.Kiminini	Upper Midland Zones (semi-humid)	UM3	0.89346	34.92562
132.Kinyoro	Upper Midland Zones (transitional)	UM4	0.99319	34.87029
133.Saboti	Lower Highland Zones (sub humid)	LH2	0.94012	34.84270
134.Sikhendu	Upper Midland Zones (transitional)	UM4		
135.Sirende	Upper Midland Zones (transitional)	UM4	0.96903	35.05195
West Pokot				
West Pokot				
136.Kaibos	Lower Highland Zones (sub humid)	LH2		
137.Kamatira	Lower Highland Zones (semi-humid)	LH3		
138.Kapkoris	Lower Highland Zones (semi-humid)	LH3	1.29171	35.11857
139.Karas	Lower Highland Zones (sub humid)	LH2	1.26445	35.13048
140.Kipkorinya	Lower Highland Zones (sub humid)	LH2	1.20904	35.13701
141.Makutano	Lower Highland Zones (sub humid)	LH2	1.25672	35.09419
142.Siyoi	Lower Highland Zones (semi-humid)	LH3	1.23811	35.14218
143.Talau	Lower Highland Zones (humid)	LH1	1.20278	35.10882

Source: (Jaetzold and Schmidt, 1983)