

REVIEW

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# Important alien and potential native invasive insect pests of key fruit trees in Sub-Saharan Africa: advances in sustainable pre- and post-harvest management approaches

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## Abstract

Fruit production in Sub-Saharan Africa is of paramount importance both socially and economically. Millions of farmers derive livelihoods from mango, avocado, citrus, cashew, and coconut farming, but native and alien invasive species constrain production. The region's capacity to contain invasives is weak due to the absence of national and institutional support systems for early detection, containment, eradication, or management of the pests. Climate change is expected to play a huge role in the influx of more alien invasive species and the shift of ecological requirements of some native species. Though a fair share of pre- and post-management pest management techniques for several insect pests has been developed, adoption and adaptation of the options are limited. Data on economic and social implications are largely lacking, making it challenging to implement informed policy decisions. The existence of the "Strategy for Managing Invasive Species in Africa 2021–2030" promises a paradigm shift in the management of invasives, from reactive thinking to coordinated proactive approaches. The uncoordinated deployment of management measures in the region and the lack of funding, play a negative role in managing the pests effectively. Prospects for enhanced future research are wide, and efforts are currently being channeled to Area-Wide-Integrated Pest Management in a bottom-up approach with stakeholders owning the process. Participatory development of technologies is also taking centre stage, paving the way for increased adoption and adaptation. Postharvest technologies promise to provide the adequate phytosanitary assurance required by countries importing fruit from Sub-Saharan Africa.

**Keywords:** Native invasive species, Alien invasive species, *Bactrocera*, Citrus, IPM, Coreid, Mealybug, Strategy

## Background

The term "invasion" often sends chills down the spines of many, due to the negative connotations associated with its meaning and origins. The word is militant, frequently denoting aggression, to take control and dominate. Such was great fear and resultant losses related to "invasion" when national armies invaded foreign powers in world war I and II. In the same vein of aggression, The British

Ecologist, Charles Elton, often recognized as the father of invasion ecology (Davis et al. 2001; Hobbs and Richardson 2010) introduced the concept of biological explosions in the ecological sense (Elton 1958). Elton noted the frequency and explosive damage associated with invaders on the mainland, islands, and even deep inside oceans was too huge to be ignored. True to his word, invasions are increasing at an alarming rate joining the world into one sphere with shared biodiversity thus diminishing the thin line between native invasive species which for the sake of avoiding debate shall be referred to as potential invasive species in this review and alien invasive species

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(AIS) (Gallardo et al. 2019; Seebens et al. 2017). The effects of invasive species are widespread ranging from biodiversity and ecosystem functioning (Chornesky and Randall 2003; Evans et al. 2016) to livelihoods (Aravindakshan 2011; Bajwa et al. 2019; Shackleton et al. 2019) and economies (Hanley and Roberts 2019; Pratt et al. 2017). Their ripple effects are cross-cutting rather than isolated, as ecosystems, livelihoods, and economies are interlinked. Invasion terminologies have of late played center stage as ideological differences pit authorities against each other especially regarding the placement of alien and indigenous species in the invasion conundrum (Colautti and MacIsaac 2004). Colautti and MacIsaac 2004 suggested “neutral terminology” for invasive species and other ecological terms, but they were biased towards the biogeographical perspective at the expense of the ecological view.

Elton 1958 recognized two forms of invasions; in which either indigenous or alien species can cause explosive effects in their native range (the case of the former) or newly established areas (the case of the latter). However, his invaders’ classic, chose to explore invasion from the point of introduced species. Various authorities have defined invasive species either in the biogeographic sense (Pysek 1995) or ecological context as alluded to in the founding principles of Elton 1958. The biogeographic perspective aligns itself with four key areas: the pest has to be alien (non-native), must establish and spread in the new area and its effects are mostly negative to the receiving ecosystem and the economy (Chornesky and Randall 2003; Pysek 1995; Wilcove et al. 1998). Pyšek et al. (2004) further argue that species that are native but spread to other areas within the same geographic locality should be referred to as expansive rather than invasive. Hence, they favor the biogeographic approach over the ecological approach. On the other hand, the ecological approach considers indigenous species as candidates for invasiveness too. The concept captures key elements of harmful incursion, encroachment, and spread, regardless of the origin being native or alien (Alpert et al. 2000). The important aspect is movement and undesirable effects in the new place. Therefore, the ecological approach ignores the aspect of how a species first arrives where it is causing devastating effects (Alpert et al. 2000). Native invasive species have been mentioned in literature for example by Valéry et al. (2009), Buczkowski (2010), and Shackelford et al. (2013).

Buczkowski (2010) argued that native species may possess invasive characteristics which enable them to expand their ecological range albeit with huge ramifications to the environment or economy. His studies provide empirical evidence that aggressive traits may evolve in species as an adaptation to prevailing environmental conditions.

Indeed, these observations have been witnessed in nature when native species occupy new habitats in their native ranges. Current attention has been on avoiding the entry by alien invaders but there is a need to introspect and take serious considerations on indigenous species that have responded to environmental cues or man-inspired changes and simply upgraded their aggressiveness.

Globalization has brought about the increased trans-boundary movement of alien invasive pests from their native ranges to completely new areas where they have since successfully established (Early et al. 2016; Fleming et al. 2017; Meyerson and Mooney 2007). In the absence of coevolved natural enemies and knowledge systems on their management, they often reproduce exponentially thus overwhelming the invaded areas. They have become one of the most single threats to agriculture on a global scale (Hobbs and Richardson 2010). Paini et al. (2016) noted that Sub Sahara Africa (SSA) was the most vulnerable region to invasion due to various factors which include dependence on agriculture and huge trade volumes with the USA and China. This is further compounded by poorly developed response mechanisms and capacities to deal with invasions. Invasive species have in the past hit hard on Africa and continue to do so at an alarming rate. One of the most affected has been the fruit and vegetable sector. Fruits and vegetables rank among the topmost produced and exported commodities from SSA (Temu and Temu 2005). The production system is mostly by smallholder farmers with millions employed at various levels of the value chain (Joosten et al. 2015; Lux et al. 2003b; Selwyn 2013). Demand for fruits is rising especially in the developed world due to consumer awareness and climatic limits (Mason-D’Croz et al. 2019; Pollack 2001; Voth 2000). This places SSA as a noteworthy contributor to fruit export. Past trends have shown that the developing world is poised to produce at least 98% of total fruit production with the developed world importing and trading more than 80% of this quantity (Maniania and Ekesi 2016; Sarris 2003).

Local consumption of fruits in SSA has also gone up tremendously mostly due to increased incomes, awareness, and availability. Global shift to healthy eating is evident in all standard family and individual meals in households. Fruits contribute quantifiable amounts of nutrients, antioxidants, and minerals which are essential for healthy living (Bergh 1992; Maldonado-Celis et al. 2019; Turner and Burri 2013). The change in consumerism and the accompanying demand continue to open up avenues and expansion of fruit production in SSA but unfortunately current and future demand is unlikely to be met considering limitations imposed by various biotic and abiotic factors. Potential economic and nutritional benefits can only be fully unlocked if existing bottlenecks

are addressed holistically (Jamnadass et al. 2011). Among these constraints are invasive insect pests which wreak havoc during production and their effects are felt at the pre-and postharvest stages (Ndlela et al. 2017). Both AIS and potential native invasive species continue to wreak havoc in tree crops thus heavily impacting ecological relationships and sources of income for millions of resource-poor smallholder farmers and various actors in the value chain (Ekesi et al. 2016; Graziosi et al. 2020). In the absence of clear and documented indices and metrics to quantify the effect of insect pests on fruit trees and fruit production, the huge amounts of synthetic pesticide pumped into the production system bear witness to the burden facing humanity (de Bon et al. 2014). Just like any other commodities in SSA, comprehensive data on pre-and postharvest losses in major fruit trees in terms of direct and indirect losses are hugely not available. This is attributed to unsystematic methodologies for measuring loss and poor understanding of production and value chain systems. In the face of recurring droughts and sometimes too much rain affecting traditional food and cash crops such as maize, sorghum, cotton, potatoes, and sunflower among others, fruit trees are a viable option in strategically fighting hunger and malnutrition in SSA. Fruit trees are capable of surviving droughts, require less input compared to other food and cash crops, and can bring forth huge yield provided minimal good agricultural practices are applied. However, the production of fruits in SSA is constrained by various biotic and abiotic factors, chief among them devastating AIS and potential native invasive species. These insect pests reduce both fruit yield quality and quantity before and after harvest. The immature developing stages of the pests damage

fruits by their feeding habits thus causing fruit to lose aesthetic and economic value. Stringent export markets further compound the problem through import restrictions since the concerned pests are of major quarantine importance.

This paper explored and discussed major potential and invasive insect pests (Tables 1 and 2) of mango, *Mangifera indica* L (Anacardiaceae), avocado (*Persea americana* Mill (Lauraceae), citrus (Rutaceae), cashew, *Anacardium occidentale* L (Anacardiaceae), and coconuts, *Cocos nucifera* L. (Arecaceae) in SSA and reviewed current and future strides towards the management of the pests in a sustainable manner. The main pests were identified and efforts towards their management in different parts of Africa were discussed. The pests have been conveniently placed into two groups namely alien invasive species (Table 1) and potential native invasive species (Table 2) and both represent a huge actual and potential menace in the countries in which they are currently found and are also likely to establish if conducive conditions are created. Most management measures discussed here are results of farmer participatory research thus are highly effective and environmentally benign. Figure 1 shows the distribution of AIS and potential native invasive species in SSA.

### Selected Key fruit trees of economic importance in Sub-Saharan Africa

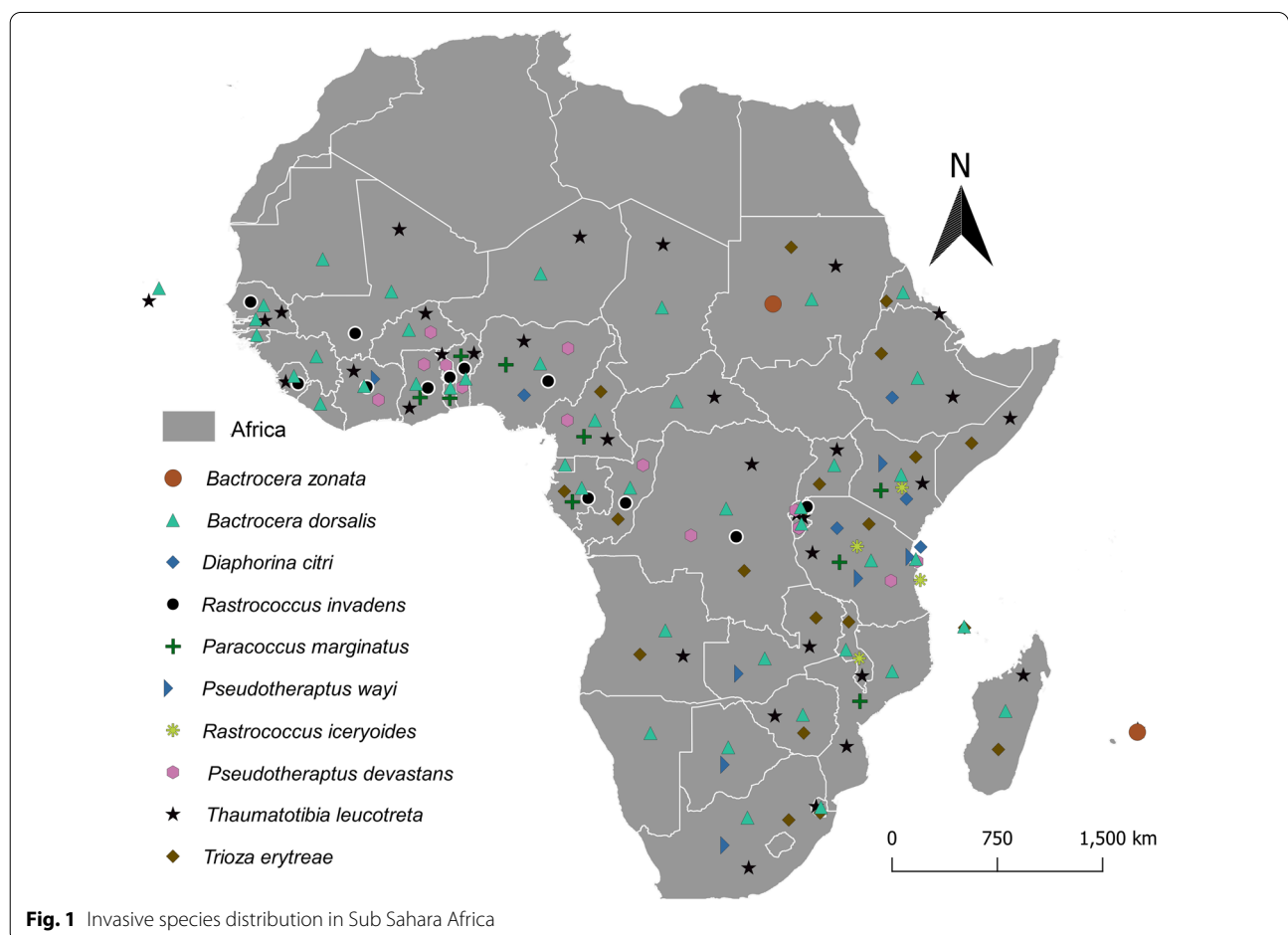
The traditional agricultural system mainly embedded in the production of cash and food crops has over the years become too vulnerable to vagaries of climate change, and increased inaccessibility of inputs particularly for resource-poor smallholder farmers in many parts of the

**Table 1** Alien invasive insect pests of fruit trees of economic importance in Sub-Saharan Africa

Genus and species	Order: Family	Country first reported	Year first reported	Major fruit trees attacked	References (first report)	Datasheets
<i>Bactrocera dorsalis</i>	Diptera: Tephritidae	Kenya	2003	Mango	Lux et al. (2003a, b), Drew et al. (2005)	<a href="https://www.cabi.org/isc/datasheet/17685">https://www.cabi.org/isc/datasheet/17685</a>
<i>Bactrocera zonata</i>	Diptera: Tephritidae	Egypt	1924	Peach, mango, and guava	Efflatoun (1924)	<a href="https://www.cabi.org/isc/datasheet/17694">https://www.cabi.org/isc/datasheet/17694</a>
<i>Diaphorina citri</i>	Hemiptera: Liviidae	Tanzania	2016	Citrus	Shimwela et al. (2016)	<a href="https://www.cabi.org/isc/datasheet/18615">https://www.cabi.org/isc/datasheet/18615</a>
<i>Paracoccus marginatus</i>	Hemiptera: Pseudococcidae	Ghana	2009	Papaya, mango, guava	Muniappan et al. (2009), Pelican News (2009)	<a href="https://www.cabi.org/isc/datasheet/39201">https://www.cabi.org/isc/datasheet/39201</a>
<i>Rastrococcus invadens</i>	Hemiptera: Pseudococcidae	Ghana	1986 (samples collected 1982)	Mango, Citrus	Williams (1986)	<a href="https://www.cabi.org/isc/datasheet/46824">https://www.cabi.org/isc/datasheet/46824</a>
<i>Rastrococcus iceryoides</i>	Hemiptera: Pseudococcidae	East Africa	1989	Mango	Williams (1989)	<a href="https://www.cabi.org/isc/datasheet/46823">https://www.cabi.org/isc/datasheet/46823</a> <a href="https://www.plantwise.org/KnowledgeBank/datasheet/46823">https://www.plantwise.org/KnowledgeBank/datasheet/46823</a>

**Table 2** Potential native invasive species of fruit trees of economic importance in Sub-Sahara Africa

Genus and species	Order: Family	Major fruit trees attacked	References	Datasheets
<i>Thaumatotibia leucotreta</i>	Lepidoptera: Tortricidae	Citrus, macadamia, Avocado, Litchi,	Daiber 1979, Erichsen and Schoeman 1992, Gilligan et al. (2011)	<a href="https://www.cabi.org/isc/datasheet/6904">https://www.cabi.org/isc/datasheet/6904</a>
<i>Pseudothraupis wayi</i>	Hemiptera: Coreidae	Litchi, macadamia, cashew, avocado	Brown 1955, Schoeman et al. (2010), Schoeman and Mohlala (2013)	<a href="https://www.cabi.org/isc/datasheet/45033">https://www.cabi.org/isc/datasheet/45033</a>
<i>Pseudothraupis devastans Distant</i>	Hemiptera: Coreidae	Coconut, cashew, avocado	Brown 1955, Doh et al. 2016; Douaho 1984	<a href="https://www.cabi.org/isc/datasheet/45032">https://www.cabi.org/isc/datasheet/45032</a>
<i>Trioza erytrae</i>	Hemiptera: Triozidae	Citrus	Samways and Manicom 1983, Van den Berg 1990, Ajene et al. (2019)	<a href="https://www.cabi.org/isc/datasheet/54914">https://www.cabi.org/isc/datasheet/54914</a>



**Fig. 1** Invasive species distribution in Sub Sahara Africa

world (DeClerck 2013). Fruit trees respond well to dry periods due to their resilient deep rooting development and farmers are assured of a harvest even under extreme weather conditions of SSA. Fruit production and marketing are projected to grow rapidly due to increased urbanization, population, and economic growth (Kehlenbeck et al. 2013; Satterthwaite 2017; Teye 2018). Even

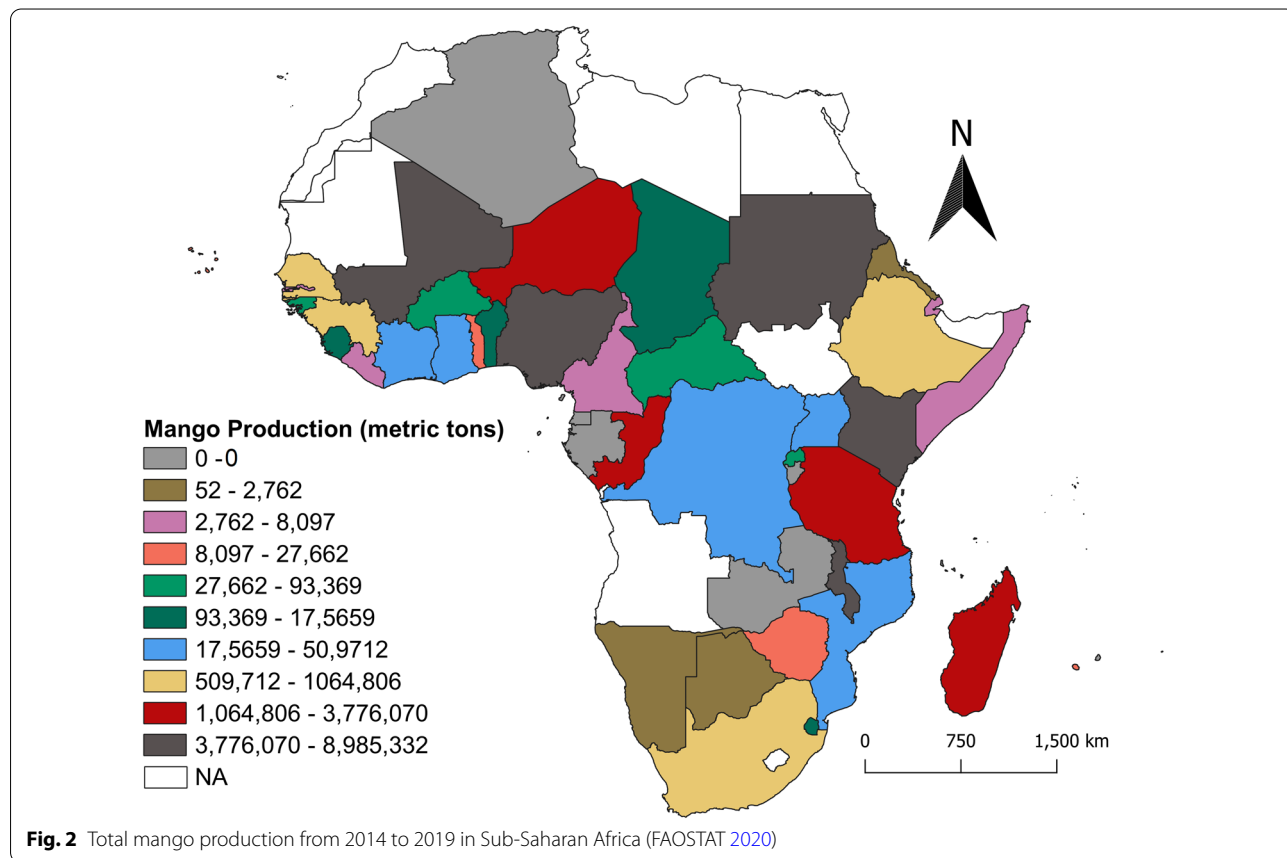
so, the benefits of consuming fruits as sources of minerals, energy, micronutrients, and vitamins are becoming more apparent and appreciated by local communities in SSA hence the imminent rise in demand (Kehlenbeck et al. 2013). Some of the major fruit trees grown in SSA include mango, avocado, citrus, cashew, and coconut. The native home of mango is tropical Asia particularly

the Indo-Burmese region (Mukherjee 1972; Rey et al. 2006), but due to trade and globalization, the tree is now established in nearly all parts of the world including SSA. Most of the production in SSA countries is done by smallholder farmers who account for over 90% of production (Van Melle and Buschmann 2013; Vaysieres et al. 2008). The trees are grown in homesteads or small orchards where little or no agronomic practices are applied. The following countries: Malawi, Nigeria, Kenya, Sudan, and Tanzania have been the major producers of mango for the period 2014–2020, (Fig. 2; FAOSTAT 2020), with most of the products exported to the Middle East.

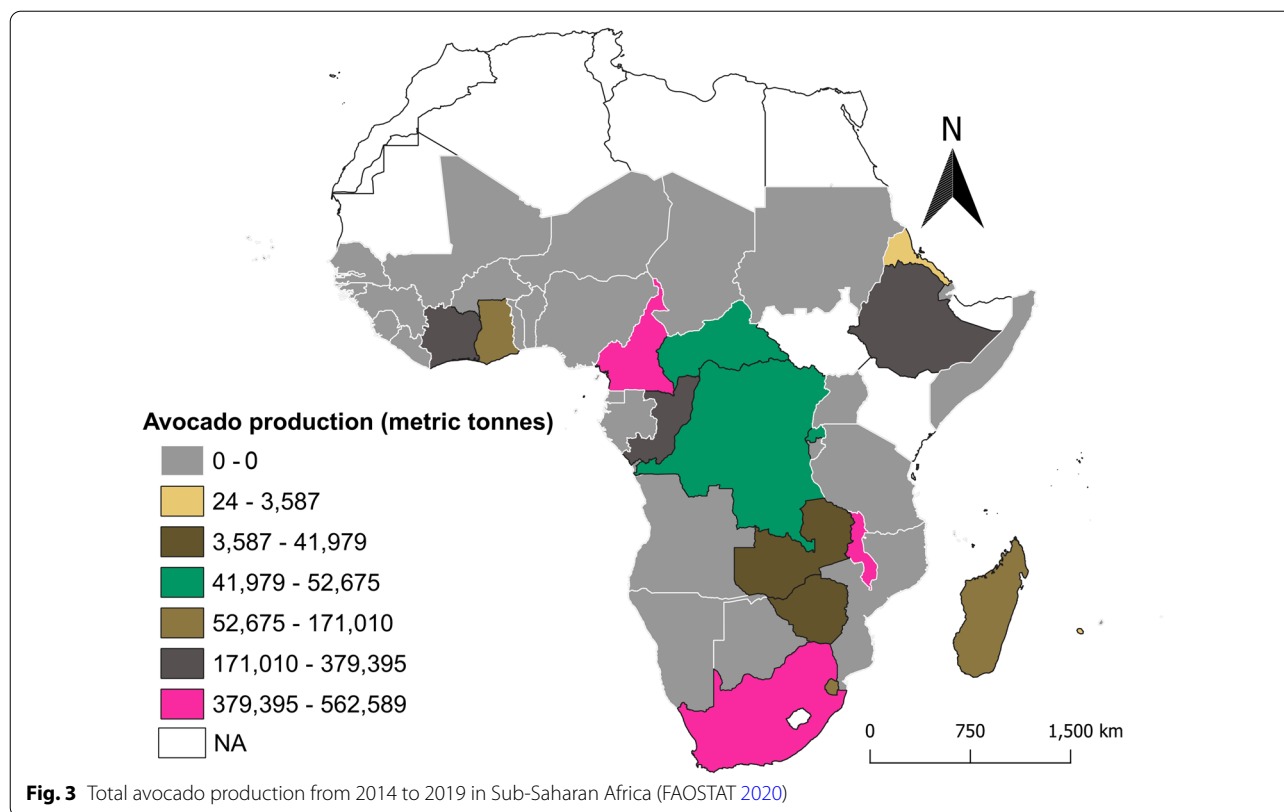
Avocado is believed to have originated in Central America and southern Mexico, later spreading to various parts of the world through trade and movement of goods and people (Chen et al. 2009; Yahia and Woolf 2011). Avocadoes are an essential source of dietary fibre, vitamins, minerals, lipids, carbohydrates, and many other essential nutrients (Dreher and Davenport 2013). The fruits are highly concentrated in phytochemicals and monounsaturated fatty acids, making avocado an excellent source of energy and nutrition (Yahia and Woolf 2011). In Africa, Kenya and South Africa are the major

producers and exporters of avocado though several countries are slowly coming up due to enhanced technology, market, and availability of suitable varieties. Top producers in SSA include Kenya, South Africa, Malawi, Cameroon, and the Democratic Republic of Congo (Fig. 3; FAOSTAT 2020). Avocado has the potential of becoming the “green gold” of SSA.

Citrus comprises several major fruit trees such as oranges, lemons, grapefruit, and lime, among others. Citrus is known to have originated in the tropical and subtropical regions of Southeast Asia, particularly the Himalayas, northeastern India, and southwest China (Gmitter and Hu 1990; Wu et al. 2018). With the advent of improved varieties, citrus is now grown in many parts of the world. In SSA, South Africa citrus production has grown tremendously over the years and ranks highest in both production and export (Moore 1962; Spreen 2010). South Africa is the largest supplier of oranges to the global market with slightly over 89 million cartons (1 carton = 15 kg) having been exported in 2019 (Citrus Growers’ Association 2020). Citrus fruits are highly rich in numerous micro- and macronutrients such as minerals, vitamin C, dietary fibre, simple sugars, and polyphenolic secondary metabolites such as flavonoids (Bermejo







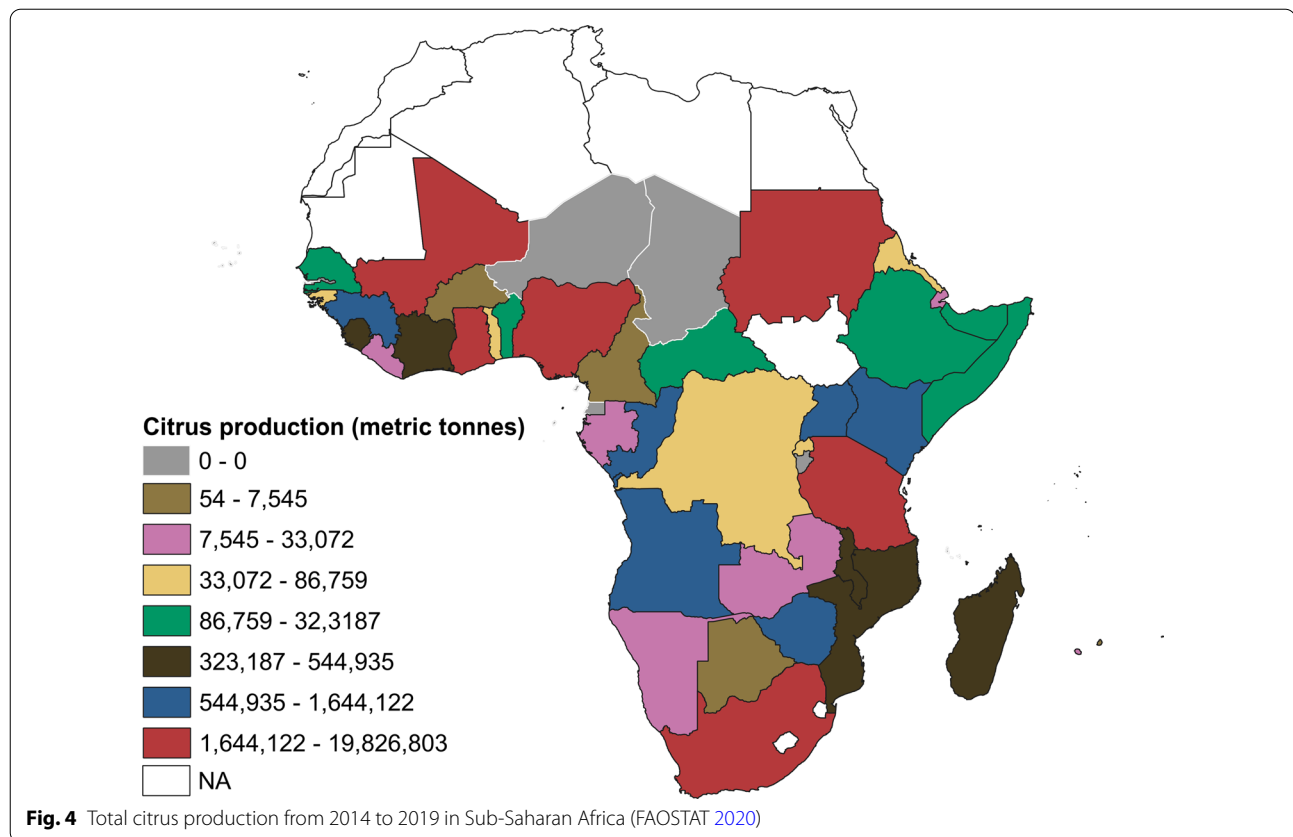
and Cano 2012; Liu et al. 2012). Grafting technology has allowed the trees to be grown almost anywhere in SSA and the availability of citrus fruits in most local markets bears testimony to increasing production levels. In the past 6 years, Nigeria, South Africa, Sudan, Mali, and Tanzania produced more citrus than any other country in SSA (Fig. 4; FAOSTAT 2020).

Another important fruit crop is cashew. The tree is indigenous to South America specifically Brazil but was introduced to Asia (India) in the sixteenth century before spreading to East Africa in later years due to increased demand for cashew products and by-products (Morton 1961). In SSA, most of the cashew production is in West and East Africa particularly in Benin, Côte d’Ivoire, Nigeria, Ghana, Burkina Faso, and Tanzania. In southern Africa, some production is ongoing in Mozambique and cashew is among the most exported commodities in the country (Antonio and Griffith 2017). In the 70 s, Mozambique was the world’s largest producer of cashew, but over the years, production levels have gone down due to various reasons. Overall, West Africa accounts for almost half of the world’s production and there are indications that production is on the increase provided bottlenecks are dealt with as a matter of urgency (Monteiro et al. 2017). Countries such as Côte d’Ivoire, Benin, Guinea-Bissau, Mali, Mozambique, and Nigeria are currently

the top producers of cashew in SSA (Fig. 5; (FAOSTAT 2020). The ability of the tree to survive in marginal nutrient-deficient soils and dry weather conditions makes it an ideal alternative source for food and income (Antonio and Griffith 2017).

Finally, the coconut tree is known to have originated in the Old-World tropics, spreading to eastern Polynesia area of the east-central Pacific Ocean, Pacific coasts of Latin America, and later into South America, the south-east of the Gulf of Mexico particularly the Caribbean and the Atlantic coasts of Africa (Baudouin and Lebrun 2009; Gunn et al. 2011; Harries 1978; Ward and Brookfield 1992) The coconut tree is often referred to as the “tree of life” because of its versatility in providing food, fuel, and timber, thus providing for the livelihoods of millions of families particularly in West Africa (Abankwah et al. 2010; Oduro-Yeboah et al. 2020; Okorley and Haizel 2004).

Coconut farming is mainly practiced in the coastal areas of tropical and subtropical regions (Campbell 2006; Schuiling and Harries 1994). The topmost producers of coconut in SSA in the past 6 years have been Tanzania, Ghana, Nigeria, Mozambique, and Côte d’Ivoire (Fig. 6; FAOSTAT 2020). Global coconut production is expected to grow by nearly 18% by the year 2025, and Africa continues showing signs of contributing to this growth due to



increased local consumption and international demand in the manufacturing industry (Viffa Consult 2020).

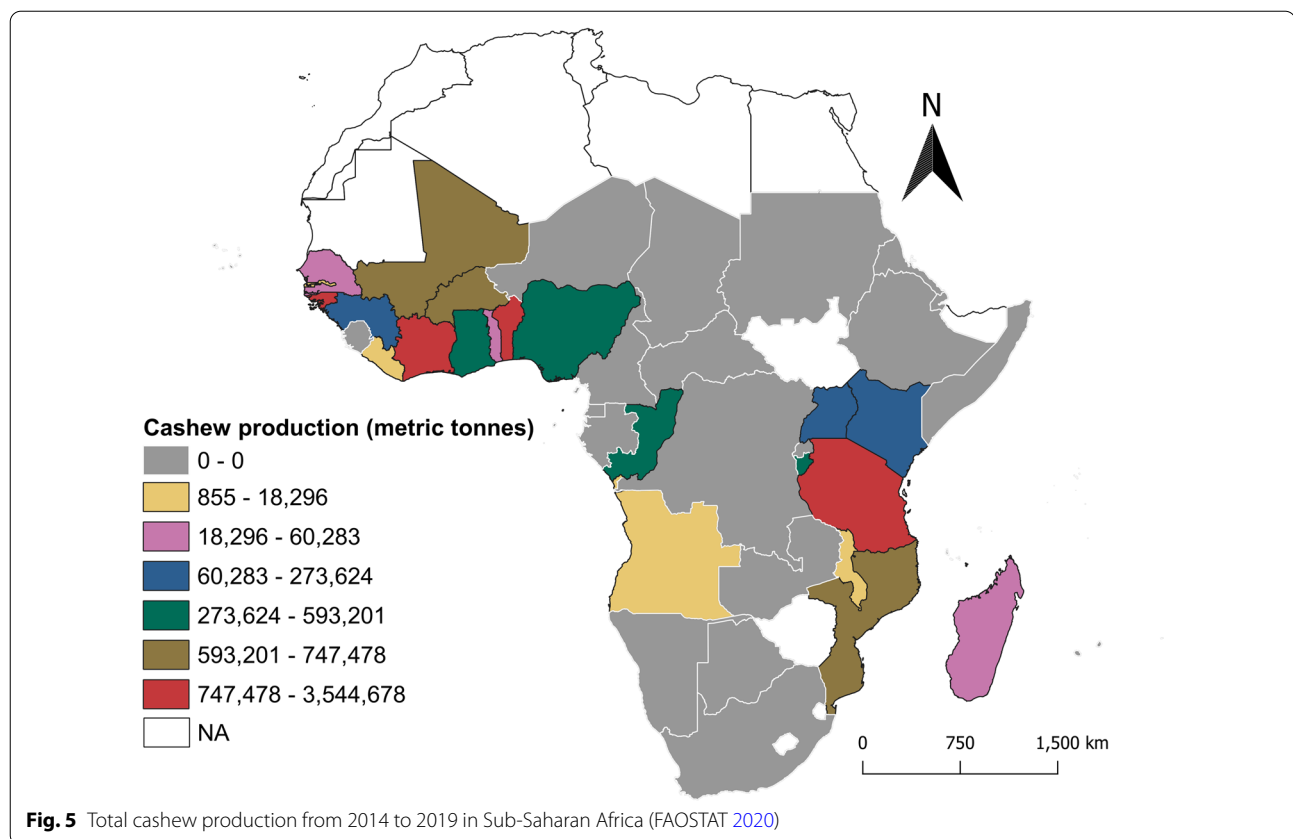
### Historical and current status of potential native invasive species and alien invasive species (AIS)

Globalization resulting from increased trade and transport links and the movement of people has resulted in a considerable surge in the occurrence and effects of insect pest invasions (Hill et al. 2016). In this review, we treat the current status of potential native invasive species and AIS, as more of a reflection of responses of the pests to ecological, physical, and anthropogenic changes than mere movement. The occurrence and impacts have further been compounded by climate change driven by human activities; a scenario projected to rise rapidly as humans take charge of primary productivity (Stone et al. 2006). The invasion by the oriental fruit fly *Bactrocera dorsalis* (Hendel) (mango and various fruits) in SSA Africa (Drew et al. 2005; Lux et al. 2003b) the peach fruit fly *Bactrocera zonata* (Saunders) (both Diptera: Tephritidae) (Peach, mango, and guava) (Eflatoun 1924; Mahmoud et al. 2020; Zingore et al. 2020) the Asian citrus psyllid *Diaphorina citri* Kuwayama (Hemiptera: Liviidae) (Citrus) (Shimwela et al. 2016), the papaya mealybug *Paracoccus marginatus* Williams and Granara

de Willink (mango, guava, and papaya) (Muniappan et al. 2009), and the mango mealybug *Rastrococcus invadens* Williams (both Hemiptera: Pseudococcidae) (mango and citrus) (Williams 1986) (see Fig. 1) has resulted in devastating ecological and economic effects to the fruit production industry and these components will be dealt with later in this paper. In addition to these AIS, various potential native invasive species have equally devastated fruit production, particularly among resource-challenged smallholder farmers. These include the false codling moth *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) (Gilligan et al. 2011), the coconut bug *Pseudotheraptus wayi* Brown (Heteroptera: Coreidae) (Schoeman and Mohlala 2013), and the African citrus psyllid *Trioza erytreae* (Del Guercio) (Hemiptera: Triozidae) (Ajene et al. 2019) (see Fig. 1).

### Cropland connectivity as a driver of the invasion

Explorers, traders, and colonial settlers in historical times brought most exotic tree species to Africa which have in present times impacted heavily on ecological, social, and economic landscapes (Alpern 1992; Rangan et al. 2012). The crops did not necessarily originate in the native countries of the explorers, traders, and colonial settlers (Manachini and Palla 2015), but some were carried along

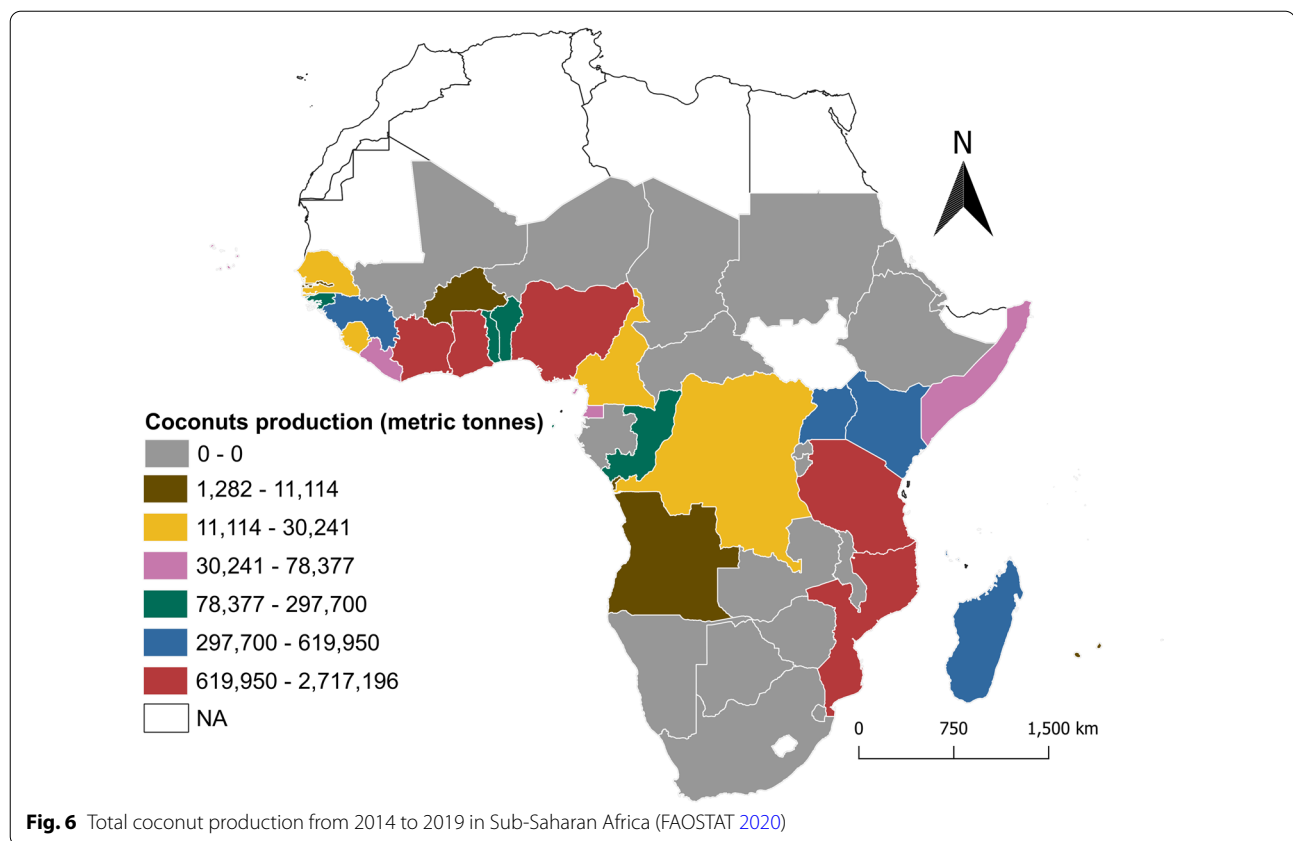


as natural collections or food from the countries they passed through in their voyages. They were also integral trade commodities, and this encouraged cultivation in many parts of the world (Heersink 1994). These exotic trees thrived unaffected in the newly established regions, producing desired yield quality and quantity as little or no pests and pathogens affected them (Manachini and Palla 2015). It was only a matter of time before insect pests were reunited with their native hosts for example the native origins of mango, avocado, citrus, cashew, and coconut can all be traced to Asia, the south, and Central America as well as the Old-World tropics in general. The invasive pests currently devastating SSA can all be traced to similar origins.

Today, mango, avocado, citrus, cashew, and coconut are grown in various parts of the world, establishing “cropland connectivity” a scenario that further creates a conduit for spread and increases the chances for survival at each stage due to the availability of a host. Cropland connectivity represents a huge risk factor for invasion (Xing et al. 2020). Though the availability of coevolved host plants plays a major role in facilitating the survival of invasive insect pests, it is important to note that AIS possess highly developed characteristic

traits which enable them to invade, spread, establish in new areas (Richardson et al. 2011) even if their native hosts are scarce. Regardless of taxa, most AIS possess high reproductive capacity (fecundity), short generation times, and high reproductive rates (Sakai et al. 2001). They can quickly change their strategies to suit the prevailing conditions thus they exhibit life-history traits adequate to adapt to climate change (Dukes and Mooney 1999). The result will be an altered ecosystem that responds to the whole global change system. Most are polyphagous, thus allowing them to survive on whatever host is available. This is true for most tephritids such as *B. dorsalis*. It sounds plausible that invasive species easily find host plants in newly invaded areas partly because they can infest new related or unrelated host plants if their native hosts are unavailable. As mentioned earlier, native species are also increasingly becoming invasive due to human-mediated activities which promote traits favoring spread and devastation (Buczowski 2010; Taylor and Irwin 2004). For example, the false codling moth is native to Africa but represents a new threat to horticulture in SSA and the world in general (Erichsen and Schoeman 1992; Gilligan et al. 2011; Mutyambai et al. 2020).





### Alien invasive species initial success: The enemy release hypothesis

The enemy release hypothesis (ERH) dates back to the turn of the twentieth century when the Swiss botanist Albert Thellung hypothesized that when alien invasive species arrive in new territories, they capitalize on the absence of their coevolved natural enemies and expand their biological and territorial accomplishment uncontrolled (Keane and Crawley 2002; Kowarik and Pyšek 2012). The invader's movement from native to foreign land acts as a temporary release from the natural host depression mechanism characterized by a dynamic oscillating pest population (Beddington et al. 1978). Notwithstanding the effect of generalist natural enemies on the invader, meaningful control will only be felt probably after some lag period when native natural enemies of related species switch hosts or co-evolved natural enemies are reunited with their host through natural or deliberate means of classical biological control (Keane and Crawley 2002).

Several studies have tested the validity of the ERH (DeWalt et al. 2004; Halbritter et al. 2012; Liu and Stiling 2006) especially on plant species and there is growing empirical evidence that the hypothesis is pregnant with interlinked unit ideas in a complicated manner

(Heger and Jeschke 2018). Current studies criticizing the ERH are inconclusive and require further evaluation under field conditions with several alien invasive species as study subjects (Heger and Jeschke 2018). However, the fact remains that the absence of specialist natural enemies may give an instant, but a short-lived window of success for the pest to perpetuate uncontrolled. Empirically proven natural enemies are often absent in invaded territories and invaders perform comparatively better than native species (Colautti et al. 2004). Nevertheless, besides the absence of natural enemies, other factors such as human-mediated activities, habitat, and climatic influences may play a major role in the observed success (Bellard et al. 2018; Colautti et al. 2004). To the best of our knowledge, none of the fruit tree pests which have invaded SSA to date came with their natural enemies. In most cases, studies on the diversity of native natural enemies effective against the new pests often yielded no positive results. For example, when the polyphagous mango mealybug *R. invadens* was reported for the first in West Africa, none of the identified native indigenous natural enemies were able to effect significant control (Agouké et al. 1988). This was also true for the oriental fruit fly *B. dorsalis* (Mohamed et al. 2006; Ndiaye et al. 2015) the

Asian citrus psyllid *D. citri* (Hall 2008), and the papaya mealybug *P. marginatus* (Goergen et al. 2014).

In the context of devastating native insect pests such as *T. leucotreta*, *P. wayi*, and *T. erytrae* the enemy release hypothesis has not been tested. We assume that since the agro-ecologies and microclimates are different, there is a huge possibility that the natural enemy assemblages may be different too. Being native does not imply the widespread occurrence of the pest's parasitoids or predators. Whether we label them as expansive (according to Pyšek et al. 2004) or invasive (according to Alpert et al. 2000), or as potential invaders the fact remains that they have expanded their ecological ranges with far-reaching adverse implications. The commodities they attack, are of economic importance within SSA and the export markets of Europe and the USA. For example, *T. leucotreta* causes huge losses in avocado and citrus thus it is considered a phytosanitary threat (Grové et al. 2010), while *T. erytrae* has recently become a local and international nuisance because of its ability to transmit the incurable citrus greening disease caused by the bacteria *Candidatus Liberibacter asiaticus* (Cocuzza et al. 2016). The coconut bug, *P. wayi* is highly polyphagous and its host range is expanding (Schoeman and Mohlala 2013) in SSA causing huge socio-economic losses (Egonyu et al. 2014). As they expand their range, it remains to be seen whether the new geophysical locations do have similar native natural enemies as the original localities or incursion sources. Mlynarek (2015) tested the enemy release hypothesis on the damselfly (*Enallagma clausum*), which is native to Canada but has been expanding its range or invading new territories. Though he concluded that the new area had far more natural enemies than the older localities, it could be possible that since the invasion distance was short, natural enemies caught up with the host faster than would happen when AIS is reported for the first time thousands of kilometers from their native ranges.

### The oriental fruit fly *Bactrocera dorsalis*

The polyphagous Oriental fruit fly *B. dorsalis* was first detected in SSA in coastal Kenya in 2003 (Lux et al. 2003b). The pest was thought to be a new species due to the wider variation in scutum and colour pattern exhibited by the Kenyan populations and was therefore identified as *Bactrocera invadens* (Drew, Tsuruta & White) (Diptera: Tephritidae). Recently, integrative taxonomic research resolved that *B. invadens* and *B. dorsalis* were the same (Bo et al. 2014; Schutze et al. 2015b) and as such were duly synonymized (Schutze et al. 2015a). Consistent with most invasive species, *B. dorsalis* rapidly spread to most African countries within 2 years of its first report in Kenya (Khamis, et al. 2009). Currently, it is fairly

distributed in SSA (Fig. 1). Its ability to adapt to various ecological and climatic conditions and wide host range in various plant families has been attributed to its rapid spread and new status as the most feared quarantine pest of economic importance (Goergen et al. 2011). Projections of *B. dorsalis* distribution under climate change are terrifying, as future distribution seemingly covers a large area of the world map (Stephens et al. 2007). The pest is highly polyphagous, attacking both cultivated and wild fruits and vegetables (Ekesi et al. 2006). In any country it has acclimatized, the pest has consistently been recorded on not less than 30 species from various families (Goergen et al. 2011; Rwomushana et al. 2008b).

Losses in mango and citrus caused by *B. dorsalis* exceed 1.7–10.6 tons per year, with Nigeria losing approximately USD 220 billion per year due to this pest (Eschen et al. 2021). Elsewhere, the annual losses are huge for example in South Africa (USD 3.2 million) and Uganda USD 116 million in mango) (Barnes et al. 2002; Nankinga et al. 2010). In Mozambique, losses exceed USD 3400 per hectare in mango orchards and may be higher in other cropping systems where growers rarely use any control measures (Cugala et al. 2020).

### The papaya mealybug *Paracoccus marginatus*

The devastating papaya mealybug, *P. marginatus* was first reported in SSA in 2009 specifically in West Africa; Ghana (Muniappan et al. 2009). Within the same year, the pest had spread to neighboring countries in West Africa, such as Benin, and Togo and it is now present in Nigeria, Senegal, Mauritania, Burkina Faso, Gabon, Cameroon, and Sierra Leone (Goergen et al. 2011). The papaya mealybug spread to the Indian Ocean Islands of Mauritius (Germain et al. 2014). East Africa i.e. Tanzania (IITA 2015), and Kenya (Macharia et al. 2017) as well as Southern Africa; Mozambique (Ahmed et al. 2015; Cugala et al. 2013). Recently it has been reported in South Sudan (Gama et al. 2020) and appears to be spreading southwards.

*Paracoccus marginatus* is a major threat to the ecological, social, and economic wellbeing of people in the countries it invades. Though the pest prefers papaya, it is extremely polyphagous, attacking horticultural crops in 142 genera and 49 families (García Morales et al. 2016). The situation is compounded by the fact that farmers practice mixed cropping of known hosts of the pest on the same pieces of land, thus ensuring continuous availability of alternative hosts for easy perpetuation (Cham et al. 2011). In Ghana alone, the papaya industry faces collapse as the unexpected outbreak caused devastating effects to the papaya growing agro-industry, with many farmers completely losing their trees to the direct effects of the pest (Pelican News 2009). Within a short period

of being reported, the pest had reduced the area under papaya production by 85% and caused yield losses of up to 65%, rendering 1700 gainfully employed in the sector jobless (Goergen et al. 2011). Upon invading Kenya, yield losses were as high as 91%, resulting from the direct effect on the plants and fruits as well as loss of market due to poor yield quality (Macharia et al. 2017). Three years down the line, it is estimated that Kenya loses more than USD 29.8 million annually to papaya mealybug damage with individual households losing between USD 51–740 depending on locality and market available to them (Kansiime et al. 2020).

### The peach fruit fly *Bactrocera zonata*

The peach fruit fly, *B. zonata* is a polyphagous pest indigenous to South East Asia but in Africa, it is currently established in Egypt (Efflatoun 1924; El-minshawy et al. 1999; EPPO 2010), Libya, Mauritius, and Réunion (Duyck et al. 2004; El Harym and Belqat 2017; White et al. 2000) and Sudan (Salah et al. 2012). Its current occurrence presents a huge quarantine threat to the greater parts of North Africa, adjacent Southern Europe (EPPO 2010), and SSA (De Meyer et al. 2007). Typical of tephritids in the *Bactrocera* genus, *B. zonata* is highly polyphagous attacking more than 50 host plants in various families (EPPO 2010). Among these are important tree crops such as mango, citrus, peach, guava, apricot, and figs (Mosleh et al. 2011). In SSA Africa, *B. zonata* has not caused huge losses in comparison to what has been reported for example in Egypt where the pest has caused damage and loss on mango, apricot, guava, and peach amounting to Euro 190 million. The SSA context is mainly due to competition from the pest's ecological homologue, *B. dorsalis* (CABI 2020). Moquet et al. (2021) reported the gradual displacement of *B. zonata* by *B. dorsalis* in La Réunion due to overlapping ecological requirements hence its effects have not been felt as would have been anticipated. Although the pest was found to be fairly widespread in Sudan, its occurrence and distribution are incomparable to those of *B. dorsalis* (Mahmoud et al. 2020). Considering the combined *r* and *k* selected strategies of *B. dorsalis* (Duyck et al. 2007; De Meyer et al. 2010), and the widespread occurrence in SSA, *B. zonata* may not pose an enormous economic threat to the fruit tree agro-industry in this region. Invasive species often exhibit combinations of *r* and *k* strategies to out-compete similar species already in the ecosystem (Duyck et al. 2007).

### The Asian citrus psyllid *Diaphorina citri*

The Asian citrus psyllid (ACP), *D. citri* is a serious pest transmitting the devastating pathogen 'Candidatus Liberibacter asiaticus' which causes the Citrus greening disease also called "huanglongbing" translated "the

yellow dragon disease" in citrus orchards and groves worldwide (Halbert and Manjunath 2004; McClean and Schwarz 1970). *Diaphorina citri* originates from Asia (Halbert and Núñez 2004) but has of late been expanding its geographical range and that of the bacteria beyond Asia (EPPO 2021). In the SSA region, the pest was first reported in Tanzania (Shimwela et al. 2016) and later in Kenya and Zanzibar (Rwomushana et al. 2017). The pest is also present in Ethiopia (Ajene et al. 2020c), Mauritius, Reunion, (EPPO 2021; Hall 2008), Nigeria (Oke et al. 2020), and probably other countries where the pest has not yet been reported officially.

Adult psyllids feed by inserting their mouthparts into young stems and leaves to suck from plant tissue, (Hall 2008) and it is during this process that bacteria are transmitted into the plant. The feeding action can pick *Candidatus Liberibacter asiaticus* from infected trees, harbour it for a long period during which the psyllid can transmit it to hundreds of healthy trees (FAO 2013). The bacteria affect the nutrient transport system of the plant by blocking the phloem vessels. This results in deformation and loss of leaves and fruits and death of the tree in severe cases (FAO 2013). Newly infested leaves usually exhibit mixed yellow and green coloration, later becoming mottled as the disease progresses (Feely 2015).

As the nymphs feed on young shoots and leaves, they produce large amounts of honeydew on which sooty mold develops, resulting in the characteristic black colour on leaves and twigs (Hall 2008). Disease transmission is more likely to occur during new leaf growth as gravid *D. citri* females prefer laying eggs on fresh shoots (Luo et al. 2015). This could be an adaptation to ensure that hatching nymphs have access to quality food upon emergence as they are largely sedentary (Tsai and Liu 2000).

In the last two decades, the citrus greening disease has arguably become the world's most devastating disease of citrus, depending on location and production system (Hall 2008). In East Africa, *D. citri* has the potential to destroy the citrus industry as farmers are currently not applying any management measures. As a result of the devastating effects being felt, some farmers are abandoning citrus orchards while others are uprooting their trees and replacing them with cash crops such as maize and beans. The magnitude of losses attributed to the citrus greening disease is wholly due to the aggressive invasive nature of *D. citri* whose imminent and potential spread currently threatens the whole of Africa (Rwomushana et al. 2017). The fact that citrus greening disease does not currently have any cure, spells out its associated socio and economic impact on citrus producers worldwide. More than 100 million trees have been affected worldwide with huge losses in fruit quality, quantity, household, and export earnings (FAO 2013). Socio-economic

losses are poorly studied in SSA but estimates elsewhere indicate a reduction of direct employment in the citrus sector by up to 39% within initial infestation by citrus greening disease (FAO 2013). Within 4 years citrus greening disease reduced citrus output in Florida by USD 4.5 billion and resulted in the loss of 8257 jobs per year (Hodges and Spreen, 2006). The future of the industry is uncertain though research is frantically looking for ways to reduce the menace (Feely 2015). The socio-economic impact of the pest and disease are likely to hit SSA hard due to the fragmented nature of citrus production as well as the lack of resources to effectively manage the two. The effects are already evident in the price hike of citrus in the market as farmers are either cutting down their trees or simply abandoning them due to lost hope.

### **The fruit tree/mango mealybug *Rastrococcus invadens***

The mango mealybug *R. invadens*, one of the most devastating scale insects of fruit tree crops, is native to Asia and was reported for the first time in the SSA region in Ghana in the early eighties (Williams 1986). The first occurrences were in 1982 on mango and other related plant species in the coastal parts of Ghana (mainly Accra) and later reported decimating mango and citrus in neighboring Togo (Williams 1986; Willink and Moore 1988). The pest has since spread to various countries in SSA and the world in general where it is known to affect more than 100 host plant species in different families and genera (CABI 2021a). Among the most affected fruit trees are mango, lime, guava, grapefruit, and sweet oranges (Ivbijaro et al. 1992).

It is currently present in Benin (Agouké et al. 1988), Burkina Faso (Dakouo et al. 2011), Democratic Republic of the Congo, Côte d'Ivoire, Nigeria (Mani et al. 1995), Gabon (Boussienguet and Herren 1992), Rwanda (IPPC 2019), Senegal, Sierra Leone (CABI/EPPPO 1998), Togo (Lohr 1984), Côte d'Ivoire (Hala et al. 2004), and possibly many other countries particularly in West Africa.

Damage to mango and citrus is a result of sooty mold developing on the copious amounts of honeydew excreted by the mealybug which deprives affected plants of photosynthetic capacity (Williams 1986). The actual feeding action on phloem does not seem to impact any major direct damage (CABI 2021a) however, in severe cases, reduction in fruit weight may occur due to heavy sucking of plant sap, the introduction of pathogens that interfere with biological processes, and of course the reduced photosynthetic area (Tobih et al. 2002).

The mango mealybug menace has been tamed but the potential socio-economic challenges associated with the pest remain real. Recent field reports indicate that populations of the pest are generally low due to successful

management (Nébié et al. 2016). Yield loss of 80% in mango have been reported in Ghana (Otoïdobia and Atouga 2009), up to 100% in Côte d'Ivoire (Hala et al. 2004) and 37% in Senegal (Fall et al. 2017). Overall, the pest can cause upwards of 90% damage under high infestation and no control instances (IPPC 2019). When the pest first invaded Ghana, export earnings from mangoes and avocados fell by 85% from USD 150,000 to a paltry USD 22,000 in 1 year (Willink and Moore 1988). Considering the significant socio-economic value of mango, citrus, avocado, and other important fruit trees which are preferred hosts, *R. invadens* presents a real threat to most SSA countries in which these tree crops are grown.

### **The mango mealybug *Rastrococcus iceryoides***

*Rastrococcus iceryoides* is a polyphagous invasive pest native to India (Mani et al. 2011; Williams 1989). The mealybug is known to attack both cultivated and wild plants (Tanga et al. 2010), with infestation confined to leaves, twigs, and fruits (Tanga 2012). Currently, in SSA, the pest is causing havoc in East Africa (Kenya and Tanzania) as well as in Southern Africa (Malawi) where crop loss can be as high as 100% (Luhanga and Gwinner 1993; Tanga 2012; Williams 1989). The problem is so serious to the extent that growers have sometimes abandoned their orchards or simply cut down trees for firewood, usually following disappointments with synthetic pesticides control which in most cases is not effective or sustainable (Tanga 2012). More on the management of this pest will be discussed later in this review.

### **The false codling moth *Thaumatotibia leucotreta***

The pest status and perception of the false codling moth recently changed due to the sudden upsurge of field infestations of fruits, vegetables, and ornamentals as well as phytosanitary interceptions in Europe (Mutymbai et al. 2020). The false codling moth is native to Africa (Dai-ber 1980; Erichsen and Schoeman 1992; Gilligan et al. 2011) but is known to occur outside its native range only in Israel (CABI 2021b; Wysoki 1986). It has been intercepted in Europe in commodities from Africa but has not been established in these parts (Gilligan et al. 2011; CABI 2021b). Opinion classifies *T. leucotreta* as an ineffective invader owing to the number of years it has been established in Israel but without any reports of its occurrence in countries neighboring Israel (CABI 2021b). It is estimated that the pest is only able to disperse about 1.5 km per cropping season hence it has been considered as a moderate disperser (Loomans et al. 2020). However, owing to its ability to adapt, and polyphagous feeding habits it poses a huge potential risk to habitats outside its native range (Gilligan et al. 2011). The chances of *T. leucotreta* being introduced into the Americas are very high



considering the increased trade and transport links from native Africa (Carpenter et al. 2007). Recently the pest was declared and listed as a quarantine pest by the Mediterranean Plant Protection Organization (EPPO) and the European Union (CABI 2021b; EPPO 2021).

The false codling moth is highly polyphagous, infesting more than 70 host plants in over 40 families which include major fruit trees such as citrus, mango, peach, avocado, macadamia, and guava (EPPO 2013). The damaging stage of the pest is the larva which penetrates and burrow inside sound fruits, only dropping to the ground to pupate in the soil at the fifth instar stage (Daiber 1979). Infested fruit subsequently drops to the ground and rots (Newton 1989). Entry wholes by the neonate larvae predispose the fruit to secondary infection by bacteria and fungus thus resulting in premature fruit drop and decay (Moore and Kirkman 2008).

The devastating *T. leucotreta* caused 80% yield loss in South Africa citrus over a short period of 5 months (Hofmeyr 2003) while 46% loss was reported on the same crop in Kenya (Mkiga et al. 2019). La Croix and Thindwa (1986) reported yield losses of 30% in macadamia in South Africa and Israel. Furthermore, more than 11% of losses have also been reported on avocados in Kenya and Tanzania (Odanga et al. 2018). As has already been alluded to, in previous sections of this review, farmers in SSA practice both large scale and smallholder farming, with smallholders having a mix of fruit trees, vegetables and ornamentals. The polyphagous pest is potentially devastating because it also affects vegetables, and other cash crops such as capsicum, maize, and cotton. Muchemi (2015) reported yield losses of up to 90% on capsicum in Kenya, while 43.8% was recorded in Cameroon on the same (Djieto-lordon et al. 2014). Solanaceous vegetables are differentially affected, with yield losses of 12% being reported in Kenya and neighbouring Tanzania (Mkiga et al. 2019). In cotton, yield losses average 20% in Uganda (Stibick et al. 2010). The false codling moth represents an impending threat to fruit and vegetable production in the world and prospects of it becoming established globally are real (Boersma 2021).

### **The coconut bugs *Pseudotheraptus wayi* and *Pseudotheraptus devastans***

The polyphagous Coreid bugs, *Pseudotheraptus wayi*, and *Pseudotheraptus devastans* are important pests of coconuts, cashew, macadamia, mango, guava, litchi, and avocado among other non-tree crops such as cassava (Egonyu 2013; Van Der Meulen and Schoeman 1994; Nyambo 2009). The two pests occur widely in tropical Africa with *P. devastans* wreaking havoc mainly in West Africa (Doh et al. 2016; Douaho 1984) and *P. wayi* restricted to East Africa (Egonyu 2013). The two coreids

are known to cause between 75–100% direct damage to shoots and flowers resulting in yield loss of 80% or more in various crops (Maniania and Ekesi 2016). For example, Van Der Meulen and Schoeman (1994) reported yield loss due to *P. wayi*, of 76.2% on avocado, while Way (1953) and Nyambo (2009) reported losses of 98.8% and 80% on coconut and cashew, respectively. In guava, the yield loss can be as much as 52.4% (Van der Meulen 1992) while on litchi 40% fruit drop has been reported in South Africa (Schoeman and Mohlala 2013). On the other hand, *P. devastans* has been reported to reduce yield in coconut by up to 80% (Doh et al. 2016; Mariau et al. 1981) and ranks among the most devastating pests of coconut particularly in Côte d'Ivoire (Dwomoh et al. 2009).

The coreid bugs (*Pseudotheraptus*) cause significant damage at low pest density, for example, only ten bugs per hectare of the crop can cause huge economic damage (Van Mele 2008). This could be a result of the direct damage inflicted when feeding and the vectoring of plant pathogens. *Pseudotheraptus devastans* damages coconuts and related fruit by its feeding effect which involves inserting the stylet into plant tissue thereby causing deformation of fruit and also abortion of flowers and young fruits (Doh et al. 2014). The bug has been implicated in the transmission of devastating viruses in cassava (Doh et al. 2014) and their stylet incisions serve as entry points for pathogenic fungi (Makambila 1994). Economic data is scanty in literature but *P. wayi* caused a combined loss of USD 86,000 worth of avocados during the 1991 cropping season (Erichsen and Schoeman 1992). The two pests continue to pose a significant threat to the tree crop industry and their effect may increase considering the rapid expansion and promotion of host plants such as avocado, and drought-resistant varieties of coconuts among other various initiatives in SSA.

### **The African citrus psyllid *Trioza erytreae***

The African citrus psyllid *Trioza erytreae* is indigenous to Africa and also occurs on the Islands of Mauritius, Madagascar, Reunion (an extensive bibliography up to the year 1987 has been given by Van Den Berg and Fletcher (1988)). In Southern Africa, it was first reported on South African citrus in 1897 (Lounsbury 1987) and later described in 1918 from lemon samples in Eritrea (Del Guercio 1918). Recently it was reported in the islands of the northwest coast of Africa particularly Madeira, thus sparking fears of its spread into mainland Europe (Carvalho and Aguiar 1997). In Europe, it is currently present but localized in Portugal and its autonomous regions of Madeira and Azores as well as Spain and the Canary Islands (Cocuzza et al. 2016; EPPO 2020; Hernández 2003). The pest once caused a dreadful loss of more than 100,000 citrus trees in the major citrus-producing



regions of South Africa, and immediate action was dispatched which revealed that the cause was the devastating greening disease (McClellan and Oberholzer 1965).

The greening disease is caused by the devastating fastidious phloem-restricted alpha-proteobacteria of the *Candidatus Liberibacter* spp. widespread in Asia, the Americas, and Africa (Shimwela et al. 2016). These are *Ca. Liberibacter africanus* (CLaf) in Africa, *Ca. Liberibacter americanus* in the Americas (CLam) and *Ca. Liberibacter asiaticus* (CLas) in Asia (Bové 2006; Halbert and Manjunath 2004; Shimwela et al. 2016). *Trioza erythrae* has been shown to transmit the Asian form of the greening disease while *D. citri* has also been shown to potentially transmit the CLaf (Ajene et al. 2019; Bové 2006; Lallemand et al. 1986). This compounds the impact and magnitude of direct and indirect socio-economic damage the two pests can cause worldwide.

The feeding effect of infected *T. erythrae* causes physical and physiological disorders in affected plants such as stunting, dieback of twigs, leaf and fruit drop, and poor fruit quality (Oberholzer et al. 1965). Characteristic damage includes open gall-like structures on leaves, severe chlorosis and curling, and copious amounts of honeydew excreted by the nymphs as they feed (Catling 1973; Cocuzza et al. 2016 and references therein).

Though the African citrus greening diseases are not as destructive as the Asian form, both the diseases and the pests remain of economic and social importance (Rasowo et al. 2019). Kilalo et al. (2009) reported farmer perceptions of between 10 and 15% damage in citrus orchards in Bungoma and Machakos counties in Kenya, while Ekesi (2015) reported heavy infestation between 31 and 52% of citrus by *T. erythrae* in the low and highland citrus-producing areas of Kenya.

### Invasive species as drivers of biodiversity loss

Invasive species have been identified as one of the most serious sources of biodiversity loss worldwide (Bellard et al. 2018). Their impacts do not only result in population decline and fluctuations, but species extinction occurs in worst-case scenarios (Pejchar and Mooney 2009). Current ecological knowledge may not be adequate to deal with these grave effects considering the unpredictability of invasions (Chornesky and Randall 2003). In the words of Charles Elton, the world is faced with serious ecological explosions whose effects can be termed impressive, of course in the negative sense (Elton 1958). Following the detection of *B. dorsalis* in Kenya in 2003 (Lux et al. 2003b), the pest quickly multiplied and spread, displacing *C. cosyra* to become the major pest of mango (Ekesi et al. 2009). Before the arrival of *B. dorsalis* in Africa, *Ceratitidis cosyra* (Walker), was the predominant pest of mangoes (Lux

et al. 2003a) but has been displaced through resource pre-emption and associated aggression (Rwomushana et al. 2008b). *Bactrocera dorsalis* is reported to have modified the fruit fly species assemblages in Comoros and there are fears that extinction of poorly competing species could be the result (Hassani et al. 2016). Dominance by *B. dorsalis* especially in the mango agro-system has been documented in several countries for example Ethiopia (Massebo and Tefera 2015), Ghana (Adzim et al. 2016), Benin (Hanna et al. 2020), Nigeria (Ugwu 2019), (Sidahmed et al. 2014) and Mozambique (Bota et al. 2018). Competitive displacement and possible extinction are not peculiar to SSA but have been recorded in other parts of the world for example in La Réunion, the arrival of *B. dorsalis* in 2017 caused a significant reduction in *B. zonata* populations 2 years later (Moquet et al. 2021). Competitive displacement also occurred in French Polynesia where *B. tryoni*, and *B. kirki* were displaced by the Oriental fruit fly (Leblanc et al. 2013). Unless niche partition occurs, and inter-specific competition is intense, competitive displacement may result in species extinction at the local level (Reitz and Trumble 2002).

Alien invasive species are also known to impact ecological ecosystem services in a diverse and complex manner most notably the integrity of ecological associations (Charles and Dukes 2008). This effect becomes of importance to man because of the benefits derived from interactions of organisms at different levels (Charles and Dukes 2008). Mohamed et al. (2006) reported the encapsulation of the indigenous parasitoid *Tetrastichus giffardii* Silvestri (Hymenoptera: Eulophidae) by *B. dorsalis* due to the strong immune system of the latter. This is not surprising as *Bactrocera cucurbitae* (Coquillett), (Diptera: Tephritidae) (a serious pest of cucurbits in SSA) now *Zeugodacus cucurbitae* (Coquillett) (De Meyer et al. 2015) also mounted a similar immune response against the native parasitoid *Psytalia cosyrae* (Wilkinson) (Hymenoptera: Braconidae) (Mohamed et al. 2003). The immune system of *B. dorsalis* was so strong to the extent that it was encapsulating its own coevolved natural enemy *Diachasmimorpha longicaudata* (Ashmead), following efforts to reunite the two in the context of classical biological control (Mohamed et al. 2008). Parasitism of *B. dorsalis* by *P. cosyrae* can detrimentally act as a reproductive sink since the native parasitoid does successfully parasitize the invasive pest but results in no progeny due to encapsulation which is consistently 100% regardless of how parasitization occurs (Ndlela et al. 2020). *Psytalia cosyrae* can only be saved from extinction if niche differentiation occurs especially considering that hosts in field conditions are plenty and options are wide (Ndlela et al. 2020).

Invasion by pestiferous insect pests continues to rise steadily and the potential of invasion in the future is equally high. Consequently, the costs associated with their management likewise continue to rise each year. For example, worldwide expenditure on various pest control products rose by 22% between 2008 and 2016 (Atwood and Paisley-Jones 2017). The greater part of the expenditure is most likely used in response to new or established invasions by insect pests. The cost of pesticide usage in SSA is largely underestimated owing to the unregulated pesticide market and pest control systems. Studies documenting the direct and indirect environmental, economic and biological effects of insecticides usage are scarce in literature but it is evident that the impact on non-target organisms, such as human and animal poisoning, general health risks, pollution, and insecticide resistance is extremely high. A recent study by (Eschen et al. (2021), reported that although alien invasive species are topical issues in Africa and their effects on livelihoods highly felt, very little has been documented on costs being incurred by Africa. They estimated the annual cost of alien invasive species in Africa to be approximately USD 3.66 trillion, with an impact on citrus fruits estimated at a staggering USD 14.6 billion annually. This is astounding, considering that the total monetary value of goods and services (GDP) by individual African countries ranges between only USD 17–440 billion per annum.

### Management of invasive pests

Food demand in the world continues to rise drastically in response to sharp increases in population (Tilman et al. 2011). Thus the threat posed by invasive pests must be counteracted to maximize yield per area cultivated (Tilman et al. 2011). Management of invasive quarantine insect pests of tree crops is of paramount importance considering the adverse effect they have on the environment as well as the socio-economic being of people of SSA. Best practices for the management of invasive and destructive pests require stringent active actions of prevention, early detection, eradication, and control. The numerous methods employed are often credited with various levels of control or suppression of invasive insect pests (McLaughlin and Dearden 2019), and none of them qualify to be single all-weather control options. Pre- and postharvest management tactics complement each other in reducing damage on crops and the choice of whatever component to adopt depends on calculated trade-offs at the micro and macro level (Waterfield and Zilberman 2012). Efforts at control have always been met with hurdles, chief among them being a limited investment in pest management, research, and adequate technology transfer especially on tree crops ranks highly as impediments to effective control of invasive and destructive pests. The

mixed and fragmented farming systems of SSA present an unlimited supply of alternative host plants which makes it difficult to manage pests adequately. Whatever means are adopted to manage the pest, the most effective strategy must be used (Edholm et al. 2018). The current review deals with management initiated by man than natural control that occurs as a result of intrinsic and extrinsic relationships between and among organisms in various agro-systems.

### Chemical control- the option of choice in the absence of alternatives

Man has always struggled to control insect pests ever since the domestication of the first plants thousands of years ago (Gupta 2004; Pretty and Bharucha 2015). The historical and present-day benefits of synthetic pesticides are innumerable and often attributed to the spectacular immediate impact on insect pests, relative affordability, accessibility, and ease of application.

Following the invasion by *B. dorsalis* in Africa mango farmers specifically responded by indiscriminate application of broad-spectrum synthetic pesticides to control the unknown pest. Even to date, though various components of Integrated Pest Management (IPM) have been developed worldwide, the majority of small and large-scale farmers in SSA Africa still use synthetic pesticides extensively (Abdullahi et al. 2011; Korir et al. 2015; Muriithi et al. 2016; Wangithi et al. 2021). Though toxicological studies specifically for *B. dorsalis* have not been done in SSA to the best of our knowledge, farmers have been using pyrethroids (deltamethrin, cypermethrin), organophosphates (acephate, chlorpyrifos, fenitrothion, dimethoate, malathion), phenylpyrazole (fipronil) (Abdullahi et al. 2011; Akotsen-Mensah et al. 2017) and various combinations and concoctions of pesticides registered in other cropping systems. Through the various projects implemented by the African Fruit Fly Programme (AFFP) in different parts of Eastern, Western and Southern Africa, most farmers were using synthetic insecticides before they were introduced to IPM.

In Egypt where *B. zonata* has been restricted for decades, malathion, lambda-cyhalothrin, methomyl among others are being used to control the pest (Elnagar et al. 2018). In Mauritius where the pest occurs alongside *B. dorsalis*, various synthetic pesticides are used though major efforts are towards bio-friendly control using biopesticides and sterile insect techniques (Sookar et al. 2014a, b). Though spreading in Sudan, (Mahmoud et al. 2020) information on control using chemical pesticides is scarce in all the cropping systems. As has been mentioned before, this could be attributed to the fact that tree crops are rarely taken care of as done in seasonal commercial and food crops. However, insecticide resistance

by *B. zonata* to malathion has been reported (Mahmoud et al. 2020).

The invasion by *D. citri* was greeted with anguish as farmers did not know what was affecting citrus trees. They either watched as their trees died or responded by spraying unknown pesticides to salvage the remaining tree stands. In other countries for example the USA, where the pest has caused devastating effects on citrus, systemic insecticides such as neonicotinoids (imidacloprid), pyridazinone (pyridaben), and, organophosphate (profenofos, chlorpyrifos, dimethoate) have been used albeit with mixed success. In Kenya and Tanzania, some farmers have abandoned citrus production, uprooting their trees, and moving on to other crop production systems.

The fight against the papaya mealybug *P. marginatus* was met with the widespread application of major chemical groups which are commonly found in most cropping systems such as organophosphates, neonicotinoids, carbamates, and thiadiazinanes, among others (Mani et al. 2012 and references therein). However, their effectiveness is limited owing to the concealed nature of the pest, hence requiring frequent applications which harm human and environmental health. Similarly, control of the mango mealybug *R. invadens* is nearly impossible owing to the same reason mentioned for the papaya mealybug. At the height of the invasion in West Africa, desperate farmers went to the extent of applying products such as the phosphorothioate; pirimiphos-methyl registered for grain storage pests (Agouké et al. 1988). Control of another mango mealybug *Rastrococcus iceryoides* with pesticides has also been attempted, albeit with very little success resulting in efforts channeled towards biological control (Tanga 2012). In many parts of SSA, management of the false codling moth *T. leucotreta* is still done using synthetic pesticides.

The application of synthetic pesticides (particularly pyrethroids) against the coconut bug *P. wayi* and the coreid bug *P. devastans* has been the norm in controlling their dispersal in cropping systems and damage to crops (Schoeman and Mohlala 2013). However, this has been found ineffective (Schoeman and Mohlala 2013), requiring a multi-pronged approach.

The pest status and socio-economic impacts of the polyphagous false codling moth (FCM) are gaining momentum as the pest continues to cause devastating effects in tree crops, flowers and fruits, and vegetables (Mutiyambai et al. 2020). Strategies geared towards controlling the pest include components of synthetic pesticides (Malan et al. 2018). However, the development of insecticide resistance and the stringent requirements of the export market on maximum residue levels are making it difficult to rely on chemical control (Hofmeyr and Pringle 1998).

This is the case with other pests such as *B. dorsalis* as residues are being closely monitored in host fruits.

### Decision making: Pest Risk Analysis and modelling

In many cases, insect pests invade new areas where they are relatively unknown (usually the first point of contact is the smallholder farmers i.e. before the policymakers and National Plant Protection Organizations (NPPO) make official identifications). It is during this time that pests overwhelm local capacities for effective management thereby causing enormous direct losses (Huber et al. 2002). Proactivity in identifying pest risk is effective in managing uncertainty. Management options can be built upon perceived risk, and robust frameworks implemented proportional to the risk (FAO 2007). Pest risk modeling is an important scientific tool that informs policy on how to proceed, based on probabilities of pest arrival, establishment, spread, and impacts within the confines of prevailing or forecasted environmental and climatic conditions (Venette 2015).

Pest Risk Analysis is nonlinear, requiring data collection and communication throughout the three administrative stages involving initiation, pest risk assessment, and pest risk management (FAO 2007). The initiation stage is critical in identifying pests of quarantine importance and their probable invasion pathways (FAO 2004). Pest Risk Analysis is not only initiated for potential pests but also when a new pest has been identified in an area, has been intercepted, or an already established pest is suddenly reported as causing serious damage than it used to (FAO 2004). This is often followed by assessing risk to establish the pest's capacity for spreading and causing economic damage. Not all invasions go through the various stages of arrival, establishment, spread, and impact as some simply succumb to numerous biotic and abiotic factors and fail to progress to the next level and disappear without a trace (Huber et al. 2002; Williamson and Fitter 1996). The third stage deals with managing the perceived or actual risk depending on the findings of the initiation stage. Appropriate recommendations may include phytosanitary measures aimed at reducing the likelihood of entry (for perceived risk) and direct interventions aimed at managing infestations, protecting the crop, or arresting spread (FAO 2004).

Pest Risk Analysis makes use of models to interpret the various stages mentioned above. Modeling and simulation of insect populations bring about a completely new dimension in understanding ecological dynamics important for planning and management (Phillips and Dudík 2008; Plant and Mangel 1987). The idea is on detecting and responding to real and perceived threats of invasion and damage within the shortest time, with minimal costs and effects to human and environmental concerns

(Barker et al. 2020). Models make use of physical, environmental, anthropogenic and, climatic variables to relate to insect pest occurrences and assess invasion risk (Jarnevich et al. 2015). These are important variables because the success of both AIS and potential native invasive species depends on evading or adapting to obstacles posed by biotic and abiotic factors (Skendžić et al. 2021). Models invariably give estimates for the spread of invasive pests, their impacts, diversity and, impacts of climate change (Phillips and Dudík 2008). Current knowledge on ecological modeling also combines phenology and geographical information systems (GIS) in elucidating insect behavior and physiological development under real-time or simulated conditions. Both climatic considerations and cyclic or seasonal fluctuations are integral in identifying and delineating action spots and timing of action vis decision and support systems available to biosecurity agents, policymakers, and farmers (Barker et al. 2020). The currently developed tools require further improvement to continuously relevant provide real-time information for decision-making in management programs (Benhadi-Marín et al. 2020).

Ecological and phenology models for both the AIS and potential native invasive species of tree crops were developed and continue to be developed to aid in pest management. For example, well before *B. dorsalis* and *B. invadens* were synonymized, Stephens et al. (2007) predicted that *B. dorsalis* could potentially establish in most parts of the world including Africa, the Americas, and Europe. Considering the current distribution records, the pest has either established itself in these regions (the case of Africa) or has been intercepted at one point e.g. the USA (Steck et al. 2019) and Europe (Nugnes et al. 2018). Following the first report of *B. invadens* in East Africa in 2003 invasion of Africa in 2003 (Lux et al. 2003b) research quickly moved in to determine whether Africa was conducive for the pest's establishment, spread, and impact. Rwomushana et al. (2008a) showed through experimentation that temperature played a pivotal role in the development and survival of *B. invadens* (*dorsalis*) with development occurring at 15–30 °C and being arrested at 35 °C. It is the lower developmental thresholds of as low as 8.8 °C and the upper limits of 30+ °C which makes the pest devastating as these conditions are most abundant in SSA. De Meyer et al. (2010) used maxent and genetic algorithms to predict the potential distribution of *B. (invadens) dorsalis* based on the association between known occurrence records in Africa and selected climatic variables. They concluded that humidity and temperature played a huge role in determining pest population dynamics. They predicted that most of Africa were suitable for the development of *B. dorsalis*

as long as moisture and temperature were ideal. De Villiers et al. (2016) modeled the potential distribution of the pest with phenology and agricultural activities such as irrigation being the main factors. Their results were similar to Dongmo et al. (2021) who simulated the effect of temperature on phenological characteristics of *B. dorsalis* and concluded that indeed temperature plays an important role in the development and spread of the pest. The models bring an interesting dimension to the management of the pest in the face of climate change.

A decade ago, Ni et al. (2012), used CLIMEX and predicted that in as much as *B. zonata* was restricted to countries along the Mediterranean; current and future climatic conditions were suitable for its establishment in various parts of the world including the tropics and subtropics. The pest has stayed long in Egypt but was recently reported in Sudan (Salah et al. 2012) and fears are that it might be moving into sub-Saharan and Sahel regions if containment measures are not scaled up in Sudan, and borders of Eritrea, South Sudan, and Ethiopia (Mahmoud et al. 2020). Similar to *B. dorsalis*, precipitation and temperature will play an important role in the establishment of *B. zonata* away from its native range of Asia and invaded regions in north-eastern Africa. The pests are predicted to spread to most parts of East, West, and Central Africa and expand their geographical range in future climatic scenarios into Western Sahara and Southern Africa (Zingore et al. 2020). This is not surprising as the pest is currently thriving under freezing temperatures of Egypt, and tolerates temperatures up to 35 °C (Duyck et al. 2004; Zingore et al. 2020).

Following the first detection of *D. citri* in East Africa, correlative and multi-model frameworks were used to predict the potential distribution of the pest when occurrence points were overlaid on citrus growing areas (Shimwela et al. 2016). There is a huge probability that the pest will be able to spread and establish in most parts of Africa and Europe where citrus production is practiced (Shimwela et al. 2016). The host *D. citri* and the disease-causing pathogen *Candidatus Liberibacter asiaticus* (Las) often move together when conditions allow (Gutierrez and Ponti 2013). Ajene et al., 2020a, b, c) predicted that most parts of East Africa were suitable for the Las, a scary scenario considering the fragmented nature of citrus production in the region. Climate change is expected to play a huge role in the spread of *D. citri* and the associated pathogen. Predictions elsewhere in China (Wang 2019), Australia (Aurambout et al. 2009), Mexico (Torres-Pacheco et al. 2013), and globally (Narouei-Khandan et al. 2016) all point to gradual expansion in the distribution range of *D. citri* either within the current context of environmental conditions or future climatic scenarios.



Temperature studies on developmental thresholds particularly regarding reproduction and development seem to agree with these modeled trends (Hall et al. 2011).

The polyphagous papaya mealybug, *Paracoccus marginatus* with a host range of more than 200 wild and plants of economic importance has been shown through ecological models that it has great potential to spread further into Africa (particularly the Sahel region), Australia, Asia, and Central America (Finch et al. 2020). In Mozambique for example, the next 20–50 years will see *P. marginatus* distribution expanding into various parts of the country as climatic conditions become conducive (Massamby et al. 2016).

### Monitoring

Pest monitoring is a planned and purposeful act of assessing the status of a pest population at a local (farm level) or area-wide scale by collecting data on presence, abundance, distribution, and dynamics (Manrakhan 2006; Preti et al. 2004). It is an official process, an intentional survey done for a pest of interest (FAO 2016). Monitoring equips the farmer, policymaker, or regulatory body on how to proceed based on data collected. For example, the data may be used in modeling or to implement ideal management measures (Preti et al. 2004). Without pest monitoring, early warning and decision support systems would be weak and incomplete to support robust pest management programs (Prasad and Prabhakar 2012). Some techniques used in pest monitoring include the commonly used traps, physical inspection of the crop, and active collection of insect samples using devices like nets. Modern techniques such as remote sensing are also contributing to precision agriculture with quicker and more accurate ways of monitoring pests (Mahlein 2016). Since remote sensing uses image sensors and does not require the physical presence of the data collector, it is a promising technical and economic pest monitoring tool (Ennouri et al. 2020). Additionally, traditional traps, are being fitted with cameras to reduce the tiresome labor of physically inspecting them in favour of a real-time collection of data from remote locations (Preti et al. 2021).

*Bactrocera* spp., are known to be attracted to one of the most powerful paraperomones, methyl eugenol, known to men. The male fruit flies respond to and feed compulsively on methyl eugenol either in its pure commercial form or in plants that contain significant amounts of the substance (Shelly 1994; Wee et al. 2017). This behavioural response has been exploited in monitoring programs for *B. dorsalis* (Haq et al. 2014; Lux et al. 2003a) and other related species such as *B. zonata* (Mahmoud et al. 2020; Salah et al. 2012). Protein baits are also used in monitoring a wide range of fruit flies. This is based on the fact that fruit flies require protein in their diet for the

development and maturation of eggs (Hagen and Finney 1950). Various protein-based products are available for fruit flies including *B. dorsalis* and *B. zonata* monitoring such as Hym lure Nu-Lure<sup>®</sup>, Bio Lure 3Component, Torula yeast, and GF-120 among others (Ekesi et al. 2014; 2009; Manrakhan 2006; Mwatawala et al. 2006). Products made from waste obtained from the brewing industry have also been shown to be effective in monitoring (Ugwu 2019) and to this effect, such a product was commercialized in Kenya as Fruit fly Mania<sup>™</sup> (<http://www.icipe.org/news/fruit-fly-bait-production-facility-launched-kenya>) (formerly Dudulure) as was used by Ndelela et al. (2016) as a monitoring tool in male annihilation farm trials.

Monitoring *D. citric* and *T. erytrae* populations in SSA is often complex as most people rely on visual inspections which are frequently unreliable. The presence of the two pests sometimes becomes noticeable when the disease they transmit (citrus greening disease) is already at an advanced stage. In other parts of the world, monitoring using sweep nets, sticky card traps, electronic suction devices, in addition to visual inspections of tree stands are used (Aubert and Quilici 1984; Miranda et al. 2018 and references therein). Yellow sticky cards were the most effective method of monitoring the psyllids (Allan et al. 2020; Hall et al. 2010; Miranda et al. 2018).

Mealybug monitoring is mainly carried out through visual inspections (Mudavanhu et al. 2011; Walton 2003) which are often time-consuming and laborious especially in fruit trees because of tree canopy accessibility. The use of sex pheromones in monitoring mealybugs is limited owing to the inadequate sensitivity of the pests to various pheromone formulations (Tanga 2012).

Coreid bugs *P. wayi*, are best monitored through physical visual checks using known scouting techniques (Radzilani et al. 2012). Visually inspecting the vegetation surrounding the main crop has also been shown to generate additional monitoring information since the bugs tend to rest on surrounding vegetation refugia (Mizell et al. 2008). Radzilani et al. (2012) investigated the use of trap crops to trap *P. wayi* and concluded that there was a possibility of using them in monitoring for the pest, together with some species of stink bugs.

### Molecular based tools and methods for pest management

Molecular tools and techniques are available for the development and improvement of pest management tactics and strategies. This field of science has been relatively slow compared to human public health (Cusson 2008). They continue to shed more light in the fields of phylogeny analysis, taxonomy and systematics, multi-level interactions, Sterile Insect Technique (SIT), and population



structure (Aketarawong et al. 2010; Clarke et al. 2005; MacDonald and Loxdale 2004; Morales-Hojas et al. 2020; Pons et al. 2006). Molecular tools have revitalized taxonomy based on morphometric characteristics only, for example, the *B. dorsalis* complex has always sparked debate (Clarke et al. 2005; Drew and Hancock 1994). A brief section on the economic impact experienced soon after the *B. invadens* invasion is available in the review by Ekesi (2015). Many countries lost their market share within Africa and also in lucrative export markets in the EU and the USA. A review of Microsatellite markers specific to the *B. dorsalis* incursion in Africa is given by Khamis and Malacrida (2016), DNA barcoding (Khamis et al. 2012), DNA analysis, PCR and multi-locus phylogenetic analysis (Schutze et al. 2015b), and integration of morphometrics, chemical ecology, ethology and cytogenetics, and a myriad of other molecular tools (Schutze et al. 2015a) helped elucidate the origin, invasion history, population dynamics, identity and taxonomy of *B. dorsalis*. This was a result of 21 years of research to break the long-standing confusion surrounding the *B. dorsalis* species complex (Hee et al. 2015). Species identity is vital in phytosanitary matters, and management based on pest risk and potential and actual invasion pathways (Clarke 2015). The identification of *B. invadens* as a new species led to confusion on management approaches and resulted in quarantine barriers which impacted trade (Hee et al. 2015; Khamis et al. 2012). The impetus to correctly identify the pest, which led to synonymization of *B. invadens* and *B. dorsalis* loosened quarantine and trade barriers and broadened pest management options (Schutze et al. 2015a).

As the potential of *B. zonata* to invade further into SSA, increases every day considering the global village activities and climate change (Zingore et al. 2020) data on molecular phylogeny on Egyptian species (Abd-El-Samie and El Fiky 2011) give a clue on identity and possible management from the experiences in Asia where the pest originates (Joomaye et al. 2000). Rapid diagnostic techniques for the pest using Polymerase chain reaction-restriction fragment length polymorphism (PCR-RFLP) (Mezghani Khemakhem et al. 2013) and real-time PCR (Koozhkandade et al. 2018) are available in the public domain, which can be adopted in SSA should the need arise. Management of *B. zonata* may not be so different from that of *B. dorsalis* considering that the two are closely related, belong to the same species complex based on phylogenetic analysis using next-generation DNA sequencing among other tools (Choudhary et al. 2015).

DNA sequencing and phylogenetic analysis enabled the correct identification of both the citrus greening disease and the vector *D. citri* at a time when citrus growers in East Africa had no idea of what had hit them (Ajene et al.

2020a; b; Rwomushana et al. 2017; Shimwela et al. 2016). Since the two pests are new in East Africa, the molecular generated data has been instrumental in initiating research into control measures for example in the area of understanding microbiomes (Ajene et al. 2020b). The combined effect of *D. citri* and *T. erythrae* poses challenges to growers and phytosanitary regulators across Africa and the globe. Their ability to transmit the citrus greening disease has led to the devotion of resources to better understand the pests which have become a global challenge (Wang 2019). Molecular characterization of both *T. erythrae* and its native parasitoids in South Africa was done to guide biological control programs following the establishment of the pest in Europe (Pérez-Rodríguez et al. 2019). Molecular PCR-based methods were developed to screen potential predators of the pest (Molina et al. 2021). In addition, endosymbiont diversity and phylogeny have been elucidated to guide the development of management measures in East Africa (Rasowo et al. 2021).

The papaya mealybug, *P. marginatus* was recently characterized in East Africa, using DNA sequencing and phylogenetic analysis, (Heya et al. 2020) confirming the correct identity following its detection in Kenya in 2017 (Macharia et al. 2017). The confirmation that only one haplotype of *P. marginatus* is present in Asia and Africa (Ahmed et al. 2015) removes possible phytosanitary and quarantine regulations between the two trading blocks and may pave way for harmonized management and regulatory measures.

Molecular tools were also instrumental in the harmonization of management measures in Eastern, Southern, and Northern Africa (Mkiga et al. 2021). The study revealed that there was low genetic variability in the haplotype diversity of *T. leucotreta* in South Africa, Sudan, Kenya, and Tanzania (Mkiga et al. 2021). Considering that the pest is not of similar economic importance both in countries within SSA and outside Africa, (Mutymbai et al. 2020) but is showing signs of resurgence and invasion of new territories, the development of diagnostic tools is important. The pest is constantly being intercepted in the USA and Europe (Gilligan et al. 2011), and may soon be established in these regions. Recent reports of the pest in West Africa, in Nigeria, following the first report eight decades ago, have led to a renewed need to correctly identify the pest to deploy effective management measures. DNA barcoding showed that Nigerian populations were consistent with East and South African haplotypes and the authors recommended similar management approaches as are already being used in Kenya and South Africa (Onah et al. 2016).

The overall role of molecular diagnostics techniques is invaluable in modern-day biosecurity in the global

village. Morphological decisions are usually based on adult identification yet quarantine and regulatory agencies require real-time or at least immediate results on pest identification to curb potential risks and economic losses. Invasive species pose the single most potential devastation to modern agriculture and associated livelihoods. Hence the need for standard, flexible, and relatively affordable molecular diagnostic tools for rapid and correct identification of invasive species (Armstrong and Ball 2005).

### Sterile Insect Technique (SIT)

The Sterile Insect Technique (SIT), has been in existence for over nine decades now and has been perfected to control several insect pests of economic importance, among them pests of fruit trees such as various tephritid fruit flies, and false codling moth (Klassen et al. 2021). The technique is based on genetic manipulation of male insects such that when sterilized by ionizing radiation, they are unable to fertilize females thus leading to population suppression or eradication (Knipling 1955). In modern phytosanitary terms, SIT has been defined as a component of IPM, aimed at releasing sterile insects in an initiative way, to suppress wild populations of the same species (FAO 2007). To date, the technology has been applied on six continents albeit at different magnitudes and for different pests. A historical review of SIT is given by (Klassen et al. 2021) and related principles and practices by several authors are contained in (Dyck et al. 2021).

Following the first detection of *B. dorsalis* in Mauritius in 1996, various control measures were rapidly implemented to contain and eradicate the pest (Seewooruthun et al., 1998). These measures included SIT, baiting, male annihilation technique (MAT) and in 2 years the pest was successfully eradicated, only to resurface 15 years later (Sookar et al. 2016). Motivated by the success of eradicating *B. dorsalis*, resources were channeled to replicating the same in eradicating another invasive fruit fly species of Asian origin, *B. zonata* (Sookar et al. 2006). Artificial rearing media and other protocols are being developed for successful SIT implementation (Sookar et al. 2014a, b). The protocols are being perfected through an International Atomic Energy Agency (IAEA) funded Coordinated Research Project (CRP) on Assessment of Simultaneous Application of SIT and MAT to Enhance *Bactrocera* Fruit Fly Management launched in 2019. The International Centre of Insect Physiology and Ecology (*icipe*) is participating in this project to establish ways for the simultaneous application of SIT and MAT in the area-wide management of *Bactrocera* species. The integration of SIT, into other IPM measures, is a promising

environmentally friendly approach for area-wide management of *B. zonata* (Sookar et al. 2014a, b).

In terms of fruit fly management using SIT, South Africa launched a pilot SIT program to eradicate *C. capitata* in the Hex River Valley of the Western Cape two and half decades ago (Barnes and Eyles 2000). The initiative exposed serious challenges and requirements which may need to be addressed if Africa is to exploit the SIT in area-wide Pest Management programs.

The experiences of the fruit fly SIT, led to the development of yet another program, on *T. leucotreta* in the citrus growing region of Olifants River Valley in the Western Cape Province of South Africa (Barnes et al. 2015; Hofmeyr et al. 2015). The project was a huge success as it reduced *T. leucotreta* populations by up to 93% and postharvest losses by 38% (Hofmeyr et al. 2015). Unlike the SIT program on fruit flies, which was greatly hampered by several constraints chief among them implementation-related issues, quality control, financing, and grower buy-in and cooperation (Barnes 2016) of the false codling moth initiative is wholly owned and financed by the Citrus Growers Association (Boersma 2021).

Though the application of SIT in pest management is already being expanded to other pests such as sugar cane borers in South Africa (Barnes et al. 2015), the applicability of the technology outside South Africa and Mauritius is limited. Successful SIT implementation requires geographical isolation, usually single crop systems, huge financial investments, and embedded coordinated research and development. The resource-poor countries of SSA, the fragmented cropping systems, uncoordinated pest management activities, and the frequent lack of buy-in by growers may prove difficult for the technology to be effective.

### Use of semiochemicals

The first breakthrough in insect semiochemical science was six decades ago when bombykol (E-10, Z-12-hexadecadien-1-ol) was isolated from the female silkworm moth *Bombyx mori* L. (*Lepidoptera: Bombycidae*) (Butenandt 1959). Since then, a whole lot of evolution has happened in this field of research, with intraspecific and interspecific interactions pursued through pheromone and allelochemicals isolation (Camps and Coll 1993; Regnier and Law 1968). Various semiochemicals are currently used in IPM, specifically for monitoring, mass trapping, mating disruption, (El-Ghany 2019; Jones 2014), or most recently as deterrents (host marking pheromones) (Cheseto et al. 2018). Semiochemicals offer huge benefits to both human, animal, and environmental health if used properly. For example, they are used at relatively low concentrations, most are effective over long

ranges, are specific, and leave no detrimental residues (Heuskin et al. 2011).

The Male Annihilation Technique (MAT) has been used in suppressing field populations of both *B. dorsalis* and *B. zonata* within and outside SSA. Following *B. dorsalis* detection in East Africa, Methyl eugenol (ME) was mainly used in monitoring (Lux et al. 2003b) but later based on successful experiences from other regions, mass trapping became much popular. *Bactrocera dorsalis* (formerly known as *Dacus dorsalis* then) was successfully eradicated from the “Friendly Island” (Rota: in the south of the United States Commonwealth of the Northern Mariana Islands) (Steiner et al. 1970; 1965). Spectacular results had also been achieved earlier in the Island of Chichi Jima, Tokyo Japan when fiberboards impregnated with ME and the organophosphate Naled were distributed extensively to control *B. dorsalis* (Christenson 1963).

In SSA, the male annihilation technique has been used with much success particularly in the southeast part of Africa in the Island of Mauritius (Seewooruthun et al., 1998; Sookar et al. 2006), East Africa (Ndlela et al. 2016), Southern Africa (Grout and Stephen 2013; Manrakhan et al. 2015) and North East Africa (Mahmoud et al. 2020; Sidahmed et al. 2014). Many attempts by farmers to use this technique are mostly unreported in SSA but the popularity has grown over the years as growers can see the trapped insects, thus are convinced that the technique works. Interest is growing in West Africa as farmers seek to adopt male annihilation because of its ease of application (Kwasi 2009). The promotion of MAT is ongoing in SSA courtesy of the various activities of the African Fruit Fly Programme (AFFP) and other regional initiatives for example COMESA. The thrust of MAT in Africa is mainly on suppression rather than eradication, (Ekesi et al. 2016), except in the Islands regions of Mauritius and compartmentalized production systems of South Africa. Should *B. zonata* spread into the interior of SSA, it will be easy to extend the MAT, since the species respond well to ME (Ghanim 2013).

Semiochemicals are available for the management of *T. leucotreta* using the mating disruption or attract and kill techniques (Moore and Hattingh 2012). Attract and Kill strategies, use lures and small amounts of synthetic pesticide to attract an insect pest to a particular point where it is killed (Klick et al. 2019; Welter et al. 2005). On the other hand, mating disruption involves disrupting insect communication particularly mating behaviour leading to management of the pests (Carde 1990; Sanders 1997). An attract and kill product developed in South Africa, is currently in use in many countries but is effective only when pest pressure is low (Moore and Hattingh 2012). This brings out the importance of monitoring so that such

management measures are deployed early when pest populations are still low and building up. Mating disruption products have also shown a similar trend of diminishing efficacy as the pest population rise (Moore and Hattingh 2012). Both techniques are density-dependent and cannot be used as standalone pest management options but fit well in IPM programs (Malan et al. 2018).

Pest management options that eliminate or reduce the number of synthetic insecticides remain the priority for sustainable management of *D. citri* (Lapointe et al. 2016). However, in the area of semiochemicals, not much breakthrough has been achieved in isolating substances that could effectively attract the pest. Yellow traps are still being used without an attractant, a scenario that reduces the efficacy and specificity of trapping systems (Akse-nov et al. 2014). In the absence of pheromones, blends have been identified which can be used in attract and kill strategies. For example, formic and acetic acids elicited some olfaction responses from *D. citri* (George et al. 2016). Efforts are currently underway to evaluate various blends to achieve the same. Recently, (Martini et al. 2020) evaluated a multi-component blend composed of Dichloromethane, tricosane, geranial, methyl salicylate, geranyl acetone, 1-tetradecene, linalool, phenylacetaldehyde, (E)-beta-ocimene, dichloromethane and concluded that a formulation of this incorporating Spinosad may be effective in attracting and kill as a management option for *D. citri*. Also, other blends of terpenes have been evaluated for their efficacy in the management of particularly the African Triozid *T. erytreae* (Antwi-Agyakwa et al. 2019).

The mealybugs' *P. marginatus*, *R. invadens*, *R. iceryoides*, and Coreid bugs *P. wayi* and *P. devastans* lack robust and effective management systems using semiochemicals as has already been shown by the absence of the same for monitoring purposes. Research towards identifying semiochemicals would go a long way in the monitoring and management of pests. However, it must be noted that sex-specific semiochemicals offer limited applicability due to polyandry movement of already-mated females into attract and kill or mating disruption zones (Welter et al. 2005). The solution lies in tactics that equally affect both males and females such as the baiting technique.

### **Bait application technique (BAT)**

The bait application technology is an inexpensive environmentally friendly pest management approach that involves the use of a food substance mixed with a toxicant deployed for the suppression of insect pests (Barbara and Capinera 2008). Though the technique has become synonymous with tephritid fruit fly management, it has some application in Lepidoptera particularly in trapping (Landolt 1995) and suppression (Justiniano

and Fernandes 2020; Muddasar et al. 2017). The history of food-based attractants is adequately reviewed by Epsky et al. (2014). Of the insect pests covered in this present review, the baiting technique has been exclusively applied to the management of the tephritids *B. dorsalis* and *B. zonata*. The basis of food baits in fruit fly management is that both female and male flies require protein for egg maturation and development respectively (Hagen and Finney 1950) but it has been shown that female flies have a greater requirement than males (Vargas et al. 2002). Food baits have a slight advantage over male lures because they capture both males and females, though with a bias towards female flies (Epsky et al. 2014). However, they require frequent applications compared to male lures which can last up to 6 weeks (Revis et al. 2004). Some of the common food baits used include GF-120<sup>®</sup>, insect Bait<sup>®</sup>, Biolure<sup>®</sup>, 621 autolyzed yeast extract<sup>®</sup>, Nu-Lure<sup>®</sup>, Mazoferm<sup>®</sup>, Provesta<sup>®</sup>, Torula yeast<sup>®</sup>, Hymlure<sup>®</sup>, Fruit Fly Bait Station<sup>™</sup> and (Questlure) among many others (Ekesi et al. 2014; Manrakhan et al. 2011; Vargas et al. 2002). Recently, a food-based bait was Fruitfly Mania<sup>™</sup> was launched in Kenya (<http://www.icipe.org/news/fruit-fly-bait-production-facility-launched-kenya>) and promises to be popular among the resource-poor smallholder farmers because of its relative affordability.

The baiting technique has been used together with other techniques in area-wide management of fruit flies such as *B. dorsalis* and *B. zonata* (Seewooruthun et al., 1998; Sookar et al. 2006). In Africa, most demonstrations of bait application have not been at area-wide control but experimentation stage in orchards (Ekesi et al. 2014; Ugwu et al. 2018; Umeh and Onukwu 2011; Vayssieres et al. 2009). However, the use of the technique is widespread in SSA, for example in citrus orchards in South Africa where the M3 Fruit Fly Bait Station<sup>™</sup> has been widely tested in a farmer participatory approach (Eltazi et al. 2008; Manrakhan et al. 2010; Manrakhan and Daneel 2013; Manrakhan and Kotze 2011; Ware et al. 2003). The greatest advantage of the BAT is that it reduces the amount of pesticide pumped into the agro system because they are used as bait stations or sprayed on small portions of the tree, usually away from the fruits (Manrakhan and Kotze 2011). The toxicant in most baits is mostly an organophosphate (Seewooruthun et al., 1998) though pyrethroids have grown in popularity with growers over the years. For example, in East Africa and Southern Africa, the use of Deltamethrin has proved equally effective. Results of experiments on Spinosad as a toxicant in BAT mostly conducted outside SSA, (Vargas et al. 2002; Wang et al. 2005) have been customized to African applications due to the reduced toxicity to human and environmental health. Spinosad is a pesticide

derived from naturally occurring compounds in the bacteria *Saccharopolyspora spinosa* (Racke 2006).

Regardless of the wide application of the BAT in fruit fly management, there is a need to adapt application protocols to SSA conditions and develop relatively affordable locally produced baits to enable wide adoption by the resource-poor farmers (at least outside the commercial farms of South Africa).

### Use of parasitoid

Classical biological control is often preferred as a sustainable management option because invasive species always invade new areas without their co-evolved natural enemies. However, scientific data must be availed, on the effectiveness of native natural enemies in dealing with the new pest. Exploration and subsequent introduction of non-indigenous natural enemies can only be done if the native natural enemies are unable to cause adequate parasitism. Extensive field surveys of *B. dorsalis* host fruits did not reveal any natural enemy effective against the pest (Rwomushana et al. 2008b). The abundant parasitoid species of fruit fly native to SSA i.e., *Psytalia phaeostigma* and *Psytalia cosyrae* (Wilkinson), (Hymenoptera: Braconidae) as well as the eulophid *T. giffardii* were unable to cause meaningful parasitism because they were encapsulated by the strong immune system of *B. dorsalis* (Mohamed et al. 2006; 2003). To this effect, two parasitoid species *Fopius arisanus* Sonan (Hymenoptera Braconidae) (egg-pupal parasitoid) and *Diachasmimorpha longicaudata* Ashmead (Hymenoptera Braconidae) (larval-pupal parasitoid) were imported for testing, mass rearing, and mass release for the management of *B. dorsalis* in SSA (Mohamed et al. 2008). An in-depth review of the management of fruit flies using *F. arisanus* and *D. longicaudata* as well as other parasitoid species have been done by Mohamed et al. (2016), thus the current review will not attempt to do the same.

Regarding *B. zonata*, the native parasitoid species and *Psytalia* spp., *Aganaspis* spp, and *T. giffardianus* Silvestri (Hymenoptera: Eulophidae) was found parasitizing the pest causing up to 58% parasitism (Mahmoud et al. 2020). However, the sample sizes of host fruit were too small, and the parasitoids are generalists thus may not give specific control of the pest. In Egypt, *B. zonata* has been present for several decades and native parasitoids were unable to control it, thus *D. longicaudata*, *F. arisanus*, *Diachasmimorpha tryoni* (Cameron), and *Diachasmimorpha kraussii* (Fullaway) were imported for possible management of the pest. Early recoveries of the parasitoid were low but encouraging (Mohamed et al. 2016). *Fopius arisanus* has also been released in La Reunion for the management of the same pest (Rousse et al. 2006). Though these localities are outside SSA, the management



of *B. zonata* in SSA will be relatively easy considering that *D. longicaudata* and *F. arisanus* are already released in many parts of Africa (Mohamed et al. 2016).

The initial surveys that led to the first report of *D. citri* in East Africa, showed possible parasitism of nymphs by *Tamarixia* sp (Hymenoptera: Eulophidae), but unfortunately, no adults of the parasitoid were recovered to enable conclusive identification (Shimwela et al. 2016). At present, no classical biological control programs have been against *D. citri* initiated in SSA, but several parasitoids are effective against the pest. For example, the endoparasitoid parasitoid *Tamarixia radiata* (Waterston), was imported from India and released in the Western Indian Ocean of Reunion Island (43 years ago), and the archipelago of Guadeloupe in the southern Caribbean Sea (22 years ago) with great success (Étiennea et al. 2001). Similar success has been replicated in Texas, USA, where more than 90% reduction in *D. citri* infestation was recorded in 6 years following the release of *T. radiata* in citrus (Flores and Ciomperlik 2017). However, earlier releases in Florida (Hoy et al. 2001) had not produced such success. Another co-evolved important parasitoid of *D. citri* is the endoparasitoids *Diaphorencyrtus aligarhensis* (Shaffee, Alam and Agarwal) (Hymenoptera: Encyrtidae), also released in Taiwan, the USA, and Réunion Island (Hall 2008). More parasitoid species are thought to control *D. citri* but may need further verification to determine whether they are primary or merely hyperparasitoids (Hall 2008).

The main parasitoid species controlling the African Citrus psyllid, *T. erytrea* are the endoparasitoid *Tamarixia dryi* (syn. *Tetrastichus dryi*) (Waterston) (Hymenoptera: Eulophidae) and the endoparasitoid *Psyllaephagus pulvinatus* (Waterston) (Hymenoptera: Encyrtidae) (Catling 1969; Mc Daniel and Moran 1972). A new parasitoid species belonging to the genus *Tamarixia* has also been shown to control *T. erytrea* (Pérez-Rodríguez et al. 2019). *Tamarixia dryi* has been successfully used in classical biological control programs in Mauritius and the Reunion Island (Bové 2014; Étiennea et al. 2001 and references therein) and shows great promise for Europe (Urbaneja-Bernat et al. 2019). In all cases above, the parasitoids were sourced from South Africa, where citrus production is a huge industry in SSA. However, in Africa, their effectiveness is highly affected by hyperparasites (Catling 1969), hence they perform better when exported outside SSA for classical biological control due to the lack of these secondary parasites in invaded territories (Étiennea et al. 2001).

The use of co-evolved parasitoids has provided positive results in classical biological control of the papaya mealybug *P. marginatus* outside its aboriginal home. For example, following the first reports of the pest in Ghana, Togo,

and Benin, efforts were channeled towards importing the parasitoids *Pseudoleptomastix mexicana*, *Acerophagus papayae*, and *Anagyrus loeckii* Noyes and Schauff (Hymenoptera: Encyrtidae) from the Caribbean island of Puerto Rico (Goergen et al. 2011). The availability of these parasitoids at the Plant Protection and Regulatory Services Directorate (PPRSD), Accra, Ghana was to serve as a reservoir from which other countries in West Africa and Africa at large were to receive initial insects to start their mass releases in case of an invasion (Goergen et al. 2011). These parasitoids have been released outside SSA with success, for example in the western Pacific Ocean archipelago of Palau and the Western Pacific in Guam (Meyerdirk et al. 2004), Florida (Amarasekare et al. 2009), and Sri Lanka (Muthulingam and Vinobaba 2021).

Following years of devastating mango production in West and Central Africa, a parasitoid species *Gyranusoidea tebygi* Noyes (Hymenoptera: Encyrtidae) was introduced in Togo for the classical biological control of *R. invadens* (Agricola et al. 1989). This was the first attempt at controlling the pest using parasitoids in West Africa. The initiative achieved phenomenal success using minimal financial resources (Bokonon-Ganta et al. 2002; Vögele et al. 1991). A second parasitoid species, similarly obtained from India, *Anagyrus mangicola* (Hymenoptera: Encyrtidae), was introduced in Togo to complement the initial effort (Moore and Cross 1993). The parasitoid exhibited superior competitive characteristics over *G. tebygi* but unfortunately was susceptible to secondary attack by hyperparasitoids (Moore and Cross 1993). The parasitoid *G. tebygi* was later released in Gabon, Benin, Sierra Leone, Ghana, and Nigeria with good establishment and dispersal (Neuenschwander et al. 1993; Pitan et al. 2000). The parasitoid's high propensity to disperse resulted in the natural establishment in the DRC and Côte d'Ivoire without any releases (Neuenschwander et al. 1993). *Anagyrus mangicola* releases were also extended beyond Togo, into Gabon, Sierra Leone, and Benin (Neuenschwander et al. 1993).

The native parasitoids *Leptomastidea tecta* Prinsloo (Hymenoptera: Encyrtidae), *Leptomastix dactylopii* Howard (Hymenoptera: Encyrtidae), and *Anagyrus pseudococci* Girault (Hymenoptera: Encyrtidae), occur widely in East Africa, where they cause significant control of *R. iceryoides* (Tanga et al. 2015). Several parasitoids are associated with *R. iceryoides* (Tanga et al. 2021) in Asia, but only three are known to be highly specific and effective, viz *Neoplatycerus tachikawai* Subba Rao, *Praleurocerus viridis* Agarwal, and *Anagyrus chryos* Noyes & Hayat (Hymenoptera: Encyrtidae). Despite the significant parasitism, control of the invasive mealybug is still inadequate considering the heavy losses in mango in Kenya, Tanzania, and Malawi (Luhanga and Gwinner



1993; Tanga et al. 2016; 2015). The seemingly dismal control is mainly due to the high number of hyperparasitoids that attack the various primary parasitoids (Tanga et al. 2021; 2016, 2015). There is a need for augmentation programs to boost field parasitism or importation of co-evolved natural enemies from Asia if the pest is to be controlled adequately. Co-evolved parasitoids will escape the effect of hyperparasitoid native to SSA.

There are several native parasitoid species known to control the false codling moth *T. leucotreta* at the egg, larval or pupal stage (Malan et al. 2018). These include *Mintha* spp. (Diptera: Tachinidae), *Chelonus curvimaculatus* Cameron, *Phanerotoma curvicarinata* Cameron, *Agathis bishop* (Nixon); (all Hymenoptera: Braconidae) and *Trichogrammatoidea cryptophlebiae* (Nagaraja) (Hymenoptera: Chalcididae) and *Apophua leucotreta* (Wilkinson) (Hymenoptera: Ichneumonidae) (Malan et al. 2018; Moore 2002; Zimba et al. 2015). However, *T. cryptophlebiae*, *A. bishopi*, and *A. leucotreta* are considered effective with *T. cryptophlebiae* being commercially mass-produced for augmentation mostly in citrus farms in South Africa (Moore 2002; Newton and Odendaal 1990). The simultaneous use of parasitoids and Sterile Insect Technique is currently being pursued as it offers synergistic control of *T. leucotreta* (Bloem et al. 2007).

CABI (2020) lists *Anastatus* Motschulsky, (Hymenoptera: Eupelmidae) *Ooencyrtus*, *Ooencyrtus utetheisae* Ashmead (Hymenoptera: Encyrtidae), *Trissolcus* spp. (Hymenoptera: Scelionidae) as egg parasitoids of *P. wayi*, but literature is lacking on the deliberate use of these natural enemies in controlling the pest. Oswald (Oswald 1990) reports *Ooencyrtus albicrus* (Prinsloo) and *Anastatus* spp. (Hymenoptera: Eupelmidae) in Zanzibar. Unfortunately, due to a lack of rearing protocols, *Anastatus* spp. could not be verified as either a primary or secondary parasitoid (Oswald 1990). Adults of *O. albicrus* were released at a micro-scale and results were encouraging. To improve *P. wayi* management, the native parasitoids can be reared in the laboratory and released to boost natural parasitism in the field. Two parasitoid species *Ooencyrtus albicrus* (Prinsloo) (Hymenoptera, Encyrtidae) and *Ooencyrtus congensis* Ashmead (Hymenoptera: Encyrtidae) are known to attack eggs of *P. devastans* (CABI 2019). However very little has been done regarding deliberate control of the pest using these parasitoids as most work has concentrated on biological control using the weaver ant (CABI 2020; Fataye and Taffin 1989).

### Use of predators

The control of *Icerya purchasi* Maskell (Hemiptera: Margarodidae), a devastating pest of citrus and acacia among other hosts using the predator *Rodolia cardinalis* (Coleoptera: Coccinellidae) was a landmark example

of successful classical biological control particularly in California and the world in general (De Bach 1964; Luff 1983). Though historical cases of biological control of insect pests using predators such as both vertebrates and invertebrates are known from the oral tradition and limited documentation, the work of Riley, Coquillett, and Koebele to save the California citrus industry from imminent destruction remains outstanding (Doutt 1958). When *B. dorsalis* invaded SSA and was presumed to be a new fruit fly species later described as *B. invadens* (Drew et al. 2005), no proven management options for the pest were known at that time since it was novel and alien (Vayssières et al. 2005). Van Mele et al. (2007) reported that mango farmers who tolerated the vicious African Weaver Ant, *Oecophylla longinoda* (Latreille) (Hymenoptera: Formicidae), had better management of the invasive pest and subsequently harvested superior quality fruit. In trees where the weaver ant has nests, *B. dorsalis* activity is substantially reduced and infestation is curtailed (Diamé et al. 2015). Ant effect is mainly attributed to both direct and indirect effects involving predator-prey interactions and olfaction (Migani et al. 2017). An account of the management of fruit flies using the weaver ant in Africa is given by Vayssières et al. (2016), while a historical review of the ant was previously done by Van Mele (2008).

Weaver ants have also been useful not only in mango, but also in other tree crops such as coconut, citrus, and cashew (Van Mele et al. 2007). Ants such as *O. longinoda* benefit from the honeydew secreted by the mealybugs but have also been shown to be predatory on nymphs and adults of the pest (Tanga 2012). The ants are predominant in the coastal part of Kenya and Tanzania where they control both fruit flies and mealybugs in mango trees (Tanga 2012). Where the ant is present in Africa, it occurs naturally as a generalist predator and has not been used intentionally in biological control programs except in West Africa where it was introduced intentionally for the management of pests in tree crops such as mango and cashew (Van Mele 2008). The historical review of the weaver ant by Van Mele (2008) cites the possible use of the predator in Zanzibar for the possible management of coreid bugs but details are lacking. Significant control of the coreid coconut bug *P. wayi* in East Africa is detailed by Vanderplank (1960) and mentions that the ant occurs widely in East, South, and West Africa.

Acceptance of the weaver and has been met with mixed feelings due to its aggressive nature, tending of mealybugs, incompatibility with parasitoids (Appiah et al. 2014; Dwomoh et al. 2009; Van Mele and Truyen 2002; Migani et al. 2017; Sinzogan et al. 2008). The demand for organic fruits from West African countries to the EU has seen an increase in *O. longinoda* husbandry, creating hope that a

balance may be found in which the full potential of the weaver ant can be attained (Van Mele 2008).

Several predators are known to attack the devastating psyllids *D. citri* and *T. erythrae*, the mealybugs *P. marginatus*, *R. invadens*, *R. iceryoides*, the coreid bugs *P. Wayi* and *P. devastans*, and the false codling moth *T. leucotreta*. However, none of the predators are currently being used in intentional coordinated pest management programs. The reason could be that most of these predators are generalists and their applicability has often been questioned (Taylor and Snyder 2021). If mass-reared and integrated into pest management programs, they pose a greater risk to non-target organisms especially due to their non-specificity (Crowder and Snyder 2010). This leaves them only applicable in controlled environments such as greenhouses, making them irrelevant in tree crops farming which is open fields and often occupying vast lands (Luff 1983). Most assessments for predator effectiveness have been conducted in experimental conditions and results are far from what transpires at the ecological level, hence many predator–prey and multilevel interactions are left unexplained (Furlong and Zalucki 2010).

### Use of entomopathogens

The negative effects associated with synthetic pesticides have pushed pest management to alternative options such as the use of entomopathogens. This has been aided by technological improvement in production techniques as well as acceptance of entomopathogens in their wide application spectra in agriculture (Samson et al. 2013). Pathogens to insect pests include fungus (Ekesi et al. 2007), bacteria (Ruii et al. 2013), nematodes (Kaya and Gaugler 1993), and viruses (Falcon 1976; Kalha et al. 2014). The technique makes use of natural relations between the insect and pathogen, thus posing no negative human or environmental health concerns if managed properly (Engler and Rogoff 1976). The use of entomopathogens was touted as the new generation of environmentally friendly and effective microbial insecticides slightly over four decades ago, Ignoffo (1975) and with the advancement of modern technology, their applicability has increased (Sandhu et al. 2017), particularly in Africa.

The relevance of Entomopathogenic nematodes (EPNs) has gained momentum over the years partly due to their effectiveness in orchards (Griffin et al. 2005), compatibility with other IPM tools, and improved modern formulation technology, which eases application (Belien 2018). Their use in pest management in SSA is still limited, except in South Africa where research and application are growing mainly due to the financial support of growers. For example, EPNs research has been on the potential use of the two obligate parasites from the genera

*Heterorhabditis* spp. and *Steinernema* spp. (Griffin et al. 2005; Kaya and Gaugler 1993) in the management of the sugar cane stalk borer *Eldana saccharina* (Pillay et al. 2009), *T. leucotreta*, (Malan et al. 2018, 2011), the citrus mealybug, *Planococcus citri* (Risso) (Hemiptera: Pseudococcidae) (van Niekerk and Malan 2012), and fruit flies such as *C. capitata* (James et al. 2018). However, in the USA and Europe, species of *Steinernema*, and *Heterorhabditis* have been available commercially since more than three decades ago (Smart 1995). In recent times, a *Heterorhabditis bacteriophora* based product was commercialized under the name Cryptonem<sup>TM</sup> and is being produced by a South African-based Company (Malan et al. 2011). Several species of EPNs occur naturally in the soil and they have been isolated and evaluated for possible control of *T. leucotreta* with high levels of efficacy (Malan et al. 2018; Steyn et al. 2019, 2017). A review of EPNs evaluation and application has been given by Belien (2018) and Platt et al. (2020).

Significant potential control of *C. capitata* using EPNs has also been demonstrated particularly in Southern Africa, with mortality upwards of 80% being recorded in trials (James et al. 2018). *Ceratitidis rosa* Karsch larvae were also shown to be susceptible to EPNs and there is room to expand the applicability of these microbes to invasive fruit flies. Already studies in many parts of the world have shown significant susceptibility of various fruit fly species to EPNs (Toledo et al. 2006; Yee and Lacey 2003). Godjo et al. (2018) demonstrated that *Heterorhabditis* spp. was able to cause more than 90% mortality to *B. dorsalis* larvae and puparia in Benin. However, the greatest mortality was obtained at the larval than at pupal stage and high moisture content levels negatively affected mortality. Similar results were obtained in North Africa, where *Heterorhabditis* spp. and *Steinernema* spp. caused slightly less than 100% mortality of *B. dorsalis* larvae and puparia (Aatif et al. 2019). Elsewhere in Asia, *Heterorhabditis* and *Steinernema* spp. showed great efficacy against the larvae and puparia of *B. dorsalis* and *B. zonata* (Usman et al. 2021). These studies can be replicated in SSA for possible commercialization of the EPNs and incorporation into pest management programs.

The future of widespread use of EPNs will depend on many factors including demand from growers, compatibility with IPM tactics, effective production and formulations, virulence, and applicability in harsh environments (Lacey et al. 2001).

Entomopathogenic fungi (EPF) particularly in the genera *Metarhizium*, *Beauveria*, *Lecanicillium*, and *Isaria* have various applications in pest management (Rath 2000; Sharma and Sharma 2021). This is because they are relatively easy to mass-produce and highly effective (Vega et al. 2009). Besides causing direct mortality, EPFs have

been shown to cause reduced reproductive potential and overall fertility (Dimbi et al. 2013; Quesada-Moraga et al. 2006). Research on EPFs has been conducted worldwide (Alves et al. 2002; Maina et al. 2018; Rajula et al. 2020; Gul et al. 2014) and SSA has contributed a fair share of this science (Ekesi et al. 2007). Though natural infection of fruit flies is rarely observed in nature, various isolates are effective against larvae, puparia, and adult fruit flies (Ekesi et al. 2005). *Metarhizium anisopliae* (Metsch.) Sorokin and *Beauveria bassiana* (Balsamo) Vuillemin have been shown to be effective against *C. cosyra*, *C. capitata*, and *C. fasciventris* (Dimbi et al. 2003) and did not affect hymenopteran parasitoids of the pests as would happen with synthetic pesticides (Ekesi et al. 2005). It is the compatibility of natural enemies, which makes EPFs find relevance in IPM programs.

*Metarhizium acridum* was shown to be effective in suppressing populations of *B. dorsalis* by up to 80% in citrus orchards in Senegal (Faye et al. 2021). The study also demonstrated the compatibility of the EPF with parapheromones using the auto dissemination technique (Faye et al. 2021). The Auto dissemination technique has been widely used in East Africa based on the concept of horizontal transmission between sexes (Dimbi et al. 2003, 2013; Maniania and Ekesi 2016). Infected fruit flies can donate and infect other individuals several days after infection, showing that inoculum is retained after first exposure, thus this could result in significant fruit fly suppression if auto dissemination devices are used (Dimbi et al. 2013; Faye et al. 2021). Besides the autodissemination device, soil inoculation under fruit trees (Ekesi et al. 2002) is another viable method of applying EPFs formulated as dust, water, or oil formulation. In Kenya, strains of *M. anisopliae* have been formulated in this way and availed commercially for fruit fly management in fruit tree orchards.

Several EPFs have been isolated and evaluated against *T. leucotreta* and mainly in citrus orchards. For example, Goble et al. (2011) evaluated the efficacy of five isolates of *M. anisopliae*, 15 isolates of *B. bassiana*, and one isolate of *Metarhizium flavoviride* (Gams and Rozsypal) against larvae and puparia of three major pests of citrus namely *T. leucotreta*, *C. capitata*, and *C. rosa*. The isolates were extremely potent against all three pests with mycosis of up to 93% being recorded on *T. leucotreta* (Goble et al. 2011). More isolates of *M. anisopliae* and *B. bassiana* were evaluated by Coombes et al. (2013) for effect against *T. leucotreta* through systematic concentration-dose and exposure-time assays and results were encouraging, thus setting the stage for possible development into commercial isolates.

Mkiga et al. (2020) evaluated 17 *M. anisopliae* and five *B. bassiana* isolates against *T. leucotreta* in East Africa.

Results indicated that mortality was as high as 94%, and reproduction potential of the devastating pest was reduced by 34% with transmission between infected individuals relatively high thus paving way for possible adoption of the auto dissemination technique in IPM of *T. leucotreta* (Mkiga et al. 2020). The most potent isolate (ICIPE 69, registered commercially as Campaign<sup>®</sup>) was then evaluated for compatibility with the FCM sex pheromone Crytrack<sup>®</sup> which is available commercially and used as an attract and kill component for the management of *T. leucotreta* (Mkiga et al. 2021). The two were compatible and the EPF persisted in field conditions for 4 weeks, suppressing *T. leucotreta* adequately (Mkiga et al. 2021). Commercial isolates of *M. anisopliae* (ICIPE 69) and *B. bassiana* (BroadBand<sup>®</sup>; Eco-Bb<sup>®</sup>) and Botanigard (LAM International Corporation, Butte, MT) are available commercially and are currently being used in the control of eggs, larvae, and pupae of *T. leucotreta* in citrus orchards particularly in South Africa (Coombes et al. 2013; Goble et al. 2011; Mondaca et al. 2020).

Following the invasion of mainland Europe and the USA by *D. citri*, resources were channelled towards devising methods for managing the invasive pest. These included possible control by EPFs (Avery et al. 2009; Gandarilla-Pacheco et al. 2013). Possibilities of infecting yellow non-sticky cards were also mooted to encourage autodissemination of spores among individuals during mating or other social events (Avery et al. 2009). Further studies on *D. citri* entomopathogens particularly *Isaria* spp., *Beauveria* spp., *Metarhizium* spp., and *Cordyceps* spp. are reported in the work of Lezama-Gutiérrez et al. (2012) and Saldarriaga Ausique et al. (2017) among others. Though happening outside SSA, the studies are being replicated in some African countries as the Asian psyllid continues to invade new territories.

In East Africa, eleven isolates of *M. anisopliae* and four of *B. bassiana* were evaluated for their efficacy against *T. erytrae* (Aidoo et al. 2021). Two isolates, ICIPE 69 (already commercialized) and ICIPE 18 (Not yet commercialized) were the most potent, causing psyllid mortalities of 83 and 98% respectively (Aidoo et al. 2021).

Not much work has been done on the management of coreid bugs using EPFs, however, some *Metarhizium* isolates already commercialized i.e. ICIPE 62, ICIPE 69, and ICIPE 78 were evaluated under laboratory conditions against nymphs of *P. wayi* (Maniania et al. 2017). Results were encouraging as mortality ranged between 98 and 100, with very short lethal times of 3–7 days (Maniania et al. 2017).

The mealybugs are difficult to control using not only synthetic insecticides but also with EPFs. Excellent mortality ranging between 70 and 100% was recorded on *P. marginatus* nymphs subjected to various concentrations



of *Metarhizium*, *Lecanicillium*, and *Beauveria* spp. for different durations but was not replicated under field conditions (Banu et al. 2010). Viruses have often found their place in pest management regardless of the challenges associated with working with them. The present-day work on viruses has significantly improved from earlier efforts of isolation, propagation, and field application (Smith 1959). Their application has mainly been on Lepidoptera larvae than any other insect order (Sun and Peng 2007). Viruses are being used in South Africa for the management of *T. leucotreta* in citrus and avocado orchards. For example, commercial products such as Cryptogran™, River Bioscience, South Africa; and Cryptex (Andermatt Biocontrol, Switzerland) are currently being used in citrus production (Moore et al. 2004, 2011). Granulo viruses are sprayed on the fruits, targeting the first instar larvae before they burrow into the fruit thus formulation and application are paramount in achieving the best results (Pereira-da-Conceicao et al. 2012). Research is still ongoing to improve the efficacy of viruses against *T. leucotreta*, with the addition of adjuvants considered to enhance efficacy (Moore et al. 2015).

Lastly, the most used bacteria in pest management is *Bacillus thuringiensis* (Bt), a naturally occurring soil microbe considered safe in pest management (Raymond and Federici 2017). Sanahuja et al. (2011) have given a review of Bt research over the last 100 years, highlighting recent developments and efforts to sustain Bt relevant in pest management. *Bacillus thuringiensis* is known to affect several species of fruit flies and can be used as a component of fruit fly IPM (Gingrich 1987; Robacker et al. 1996; Toledo et al. 1999).

To safeguard the safety of people and ensure excellent efficacy against target pests, there is a need to conduct trials under field requirements in different climatic conditions, to establish sustenance, virulence, viability, and applicability of the entomopathogens. The area of viruses and bacteria is still grey and requires more inquiry.

### Field/Orchard sanitation

Sanitation is a conscious cultural control component of IPM aimed at reducing sources of infestation during and post-crop production. The practice involves complete removal and proper disposal of infected plant material to break the cycle of the pest so that pest populations in the current and future crops are reduced. Both fallen and seemingly infested, damaged, and decaying fruits still on the tree are removed and destroyed (Moore and Kirkman 2008). Sanitation is the basis on which other pest management techniques build upon because it physically removes the pest and oviposition sites, thus suppressing pest populations before the grower incurs cost in procuring pest control products.

The suppression of *C. capitata* using the SIT in South Africa's Western Cape was briefly compromised by poor sanitation resulting from the irresponsible behaviour of grapes pickers who would discard infested grapes on the ground without any regard for vineyard sanitation (Barnes 2007). Improved adherence to proper vineyard sanitation reversed the status quo and resulted in higher fruit fly suppression by SIT (Barnes 2016). *Bactrocera dorsalis* eradication was also achieved in the southern part of the country bordering Zimbabwe, through the use of various IPM components which included rigorous orchard sanitation (Manrakhan et al. 2011).

In Mauritius, *B. dorsalis* was eradicated using an IPM package that included field sanitation as an integral component of the campaign (Seewooruthun et al., 1998; Sookar et al. 2016). Sanitation is very effective in suppressing fruit flies when used with other IPM tools (Piñero et al. 2009). The practice has the least cost requirement yet it is dreaded by growers because of its laborious nature. Sanitation has also been used against *B. dorsalis* outside SSA with great success for example, in papaya orchards in Western USA (Liquidó 1993). The trial demonstrated that sanitation reduced oviposition sites for *B. dorsalis* as well as a suitable development medium for the development of larvae. It further reduced the number of adult flies moving into the orchard searching oviposition sites and mates. Sanitation can be practiced by collecting infested fruit and burying it, or by placing them in specialized structures called Augmentorium (Klungness et al. 2005). The use of black plastic bags (killing bags) in which infested fruits are placed and exposed to the sun to kill *B. zonata* larvae was demonstrated (Badii et al. 2015). The practice is well-known and is common across Africa. Solarization kills the larvae by heat (Jenkins et al. 1969) and burying ensures emerging adults are unable to crawl to the soil surface (Dhillon et al. 2005) but has the negative effect of killing parasitoids and other fruit flies natural enemies, hence the preferred method in modern IPM programs is the use of the Augmentorium which only allows the escape of parasitoids but killing fruit flies and other pests harboured in fallen fruit (Ekesi et al. 2007; Klungness et al. 2005). Use of Augmentorium in Reunion resulted in 100% sequestration of *Ceratitidis* and *Bactrocera* spp. as well as fruit fly parasitoids *F. arisanus* and *Psytalia fletcheri* (Deguine et al. 2011). Use of Augmentoria is currently being promoted in fruit fly control initiatives in Eastern and Southern Africa following releases of the two parasitoids of *B. dorsalis*, namely *F. arisanus* and *D. longicaudata* in the mango agro-system. Indeed, the practice is now widely practiced in Africa particularly for the control of fruit flies (Badii et al. 2015).



Frequent and meticulous field sanitation removes up to 75% of *T. leucotreta* larvae in infested fields (Moore and Kirkman 2008) and until recently it was the major non-chemical control method in citrus orchards in South Africa (Moore 2002). The frequency of picking infested fruit must be increased before and during peak infestations, to avoid pest population outbreaks which may render control methods ineffective or costly (Moore and Kirkman 2008). Thus monitoring is imperative to guide the further course of action. The suppression of *T. leucotreta* in South Africa using the SIT (Boersma 2021) included a strong component of sanitation in which farmers were expected to dispose of infested fruit in a responsible manner (Hofmeyr et al. 2015). However as was the case with fruit flies, SIT in the same province of Western Cape, poor sanitation by growers resulted in the reduced success of the highly expensive program of SIT (Moore and Kirkman 2008).

Management of the citrus psyllids *D. citri* and *T. erytreae* is through various options which include sanitation in citrus orchards (Van den Berg et al. 1991). Neglected orchards are known to harbour high infestations and are often sources of incursions into other orchards or areas (Aubert and Quilici 1984). However, the severe threat posed by the citrus greening disease transmitted by both *D. citri* and *T. erytreae* has resulted in new challenges regarding management efforts in East Africa, as growers abandon trees (Djeddour et al. 2021; Ekesi 2015; Rwomushana et al. 2017). This creates reservoirs for infestation and potential sources of pest outbreaks, which can be detrimental to management efforts in well-tended orchards.

Sanitation in the case of mealybugs may be a challenge as flowers, leaves, twigs, and fruit are often infested (Tanga 2012). Thus to combat *R. iceryoides* in East and Southern Africa, growers often resort to cutting down and burning trees under heavy infestation (Tanga et al. 2021; Tanga 2012). As mentioned before, this is not tenable as farmers will ultimately lose on yield volumes due to reduced area under cultivation.

### **Integrated pest management and systems approach**

Early scientists foresaw that the uncontrolled application of synthetic pesticides was bound to cause various problems especially on ecological balance (Ehler 2006). This led to the emergence of the Integrated Pest Management (IPM) movement which sought to integrate ecologically based management practices with chemical control, based on knowledge systems (Kogan 1998 and relevant references therein). Integrated Pest Management (IPM) has been defined in various ways (Prokopy and Kogan 2003) but the major tenets being the compatibility of the

tactics in reducing the target pest below the economic injury level without causing significant harm to humans and environmental health (Ehler 2006). IPM should ideally result in a reduction of synthetic pesticide use, leading to the judicious coordinated application of pesticides as and when necessary (Ehler 2006; Metcalf and Luckmann 1994). Often, the most effective strategy, based on the timing of control of the target pest reduces economic losses and subsequently becomes the option of choice (Edholm et al. 2018). Effective IPM relies on knowledge systems stretching from Pest Risk Analysis (PRA) to various forms of modeling.

Integrated Pest Management has mainly been applied at preharvest, while other factors of production and post-production are ignored. The problem with IPM is that it has concentrated so much on developing individual components of pest management independently, then trying to use them in different combinations to achieve the desired goal of managing pests (Buitenhuis 2014). The systems approach considers managing the ecosystem, attributes of the crop, and various multi-level interactions and therapeutics (Buitenhuis 2014). The systems approach seeks to reduce pest risk at both the pre-and post-harvest stages, thus considering pest management at the place of production, at the processing place (packing house), and during shipment and distribution (FAO 2016). A system approach was developed for citrus against *T. leucotreta* and South Africa which involved controls during citrus agronomic production, post-harvesting (sampling for inspection after picking and packing and during shipment (Hattingh et al. 2020). Similar approaches are also being applied in avocado production against *T. leucotreta* and fruit flies (Grové et al. 2010). Inspection and certification during production and along the chain at shipping and distribution are integral in the success of the systems approach. The approach also considers early harvesting for example in bananas and the host status of particular fruits. For example, avocado is considered a poor host of some important fruit flies (De Graaf 2009) while bananas were found to be poor hosts of *B. dorsalis* (Cugala et al. 2017). In such cases, the systems approach is expected to mitigate the risks of infestation to the concerned commodities.

### **Postharvest systems**

Postharvest losses are huge in SSA but are often underestimated or overestimated due to inadequate and in-comparative methodologies resulting in erroneous estimates (Affognon et al. 2015). Production in SSA may not be the problem, but productivity. It is estimated that SSA requires approximately USD 940 billion to eradicate hunger by the year 2050 and more than 47% of this amount will be absorbed in mitigating postharvest losses (Sarris

2003). Technologies for postharvest treatment have been evaluated but in some cases never implemented at a commercial scale due to unavailability of adequate data to support policy (Stathers et al. 2020) or simply costs associated with the technology.

Postharvest treatment for disinfesting fruits has been scarce until recently when cold treatment of temperatures less than 1.4 °C for 16 days was used to disinfect fruit flies (*C. capitata*) in export oranges (Grout et al. 2011). The treatment is effective but may subject treated fruit to cold injury, hence the temperature fluctuations must be minimized. A second treatment followed this time, on avocado infested with the invasive *B. dorsalis*. A protocol of 1.5 °C for 18 days was demonstrated as an effective treatment to provide phytosanitary assurance in avocado infested with *B. dorsalis* (Ware et al. 2012). This was in response to the closure of lucrative export markets following *B. dorsalis* incursion into Africa. Though the treatment was effective, it was deemed too long, costly, and affected the quality of fruits. The protocol was tried in Nairobi on a commercial scale but could not give good results due to electricity power cuts. Thus in the absence of stable consistent electrical power for the 18-day duration, the quality of treated fruits was affected.

Cold treatment is also available for *T. leucotreta* in citrus. Subjecting citrus to sub-zero temperatures for 16–20 days was adequate to kill immature stages of the pest (Moore et al. 2017). The developed regimes were adequate to be used during shipment. The greatest disadvantage of cold treatment is the cold injury which affects fruits especially when temperatures fluctuate. To avert cold injury caused by the above stand-alone treatment, a partial treatment at 2 °C for 18 d or 1 °C for 16 d, can be implemented as a component of the systems approach (Moore et al. 2016).

Hot water treatment has been evaluated worldwide as an effective postharvest treatment of various fruits and vegetables (Armstrong 1982; Hernández et al. 2012; Nascimento et al. 1992; Sharp and Picho-Martinez 1990). Best on some of these studies, Hot water treatment was attempted in West Africa, Burkina Faso and results were inconclusive due to quality issues post-treatment. A hot water treatment resulting in a core temperature of 46.5 °C was deemed adequate to kill immature stages of *B. dorsalis* in mango (Self et al. 2012).

Hot water treatment experiments were also conducted independently of the West Africa studies and a temperature of 46.1 °C for 68 min was considered adequate to give 100% assurance that Apple mangoes were free from *B. dorsalis* (Ndlela et al. 2017). Further studies have been conducted on Tommy Atkins mango variety and a temperature of 46.1 °C for 72–100 min was

deemed adequate to disinfect the mangoes (Mwando et al. 2021; Ocitti et al. 2021). The protocol by Ndlela et al. (2017) has since been shared with the EU through the Kenya Plant Health Inspectorate Service (KEPHIS), the regulatory body in Kenya. The notification to export mangoes based on this treatment was officially received and acknowledged. To this effect, the first consignment of Apple mango, subjected to hot water treatment was sent to Italy and passed phytosanitary requirements. This marked the re-entrance of Kenyan mangoes into the EU since 2014 when Kenya deliberately stopped exports until procedures and protocols were in place to reenter the market without fear of interceptions. There are reports that Mozambique subjects physiologically mature mangoes to hot water treatment at 47 °C for 12 min (Dohino et al. 2016). It is however not clear whether this treatment is adequate to kill all immature stages of development for *B. dorsalis*.

Sudan is currently using Vapour Heat Treatment (VHT) at their Sudanese Center for Sterilization Horticultural Exports (SCS) to treat mangoes for export. The centre was established in 2013 and it's the first of its kind in Africa and the Middle East. Mohamed et al. (2017) reported an effective regime of 99.7% humidity and mango pulp temperature of 46.7 attained in 5 h and hydro cooling for 20 min as effective in disinfesting mangoes from *B. dorsalis*.

Other postharvest treatments available for *T. leucotreta* include a Controlled atmosphere/temperature treatment system (CATTS) (Johnson and Neven 2010), ionizing radiation (Hofmeyr et al. 2016), and fumigation (Grout and Stoltz 2020).

Ionizing radiation was evaluated as a combined treatment with cold treatment in which 60 Gy of ionizing radiation followed by subjecting the fruits to cold treatment for 16 days at 2.5 °C (Hofmeyr et al. 2016). This was adequate to provide phytosanitary disinfestation of the pest. Carbon dioxide fumigation at 70% concentration for 24 h reduced infestation significantly but not completely hence a further cold treatment albeit shorter than the conventional (Grout and Stoltz 2020). The CATTS treatment is promising but requires further validation to make it applicable in commercial postharvest treatments. In their experiment, Johnson and Neven (2010), used normal air and a modified controlled atmosphere of 1% O<sub>2</sub> and 15% CO<sub>2</sub>, at two ramping heat rates: 12 and 24 °C/h and their results could be used for future research. Postharvest treatments of *D. citri*, *P. marginatus*, *R. invadens*, *R. iceryoides*, *P. wayi*, *P. devastans*, and *T. erythrae* are limited in SSA and may require more research to develop effective treatments where necessary.

## Legislation and policy

Invasive species both native invasive species and alien invasive species in the context of this review, cause enormous losses to the fruit trees as has been assessed. Despite the huge losses even at the global scale, qualitative and quantitative estimates of impacts on the economy, livelihoods, and biodiversity remain scarce (Bradshaw et al. 2016). Where studies to this effect have been conducted, they are mainly incomplete, underestimated, or overestimated often lacking systematic inclusion of all components in the interlinked system. Management measures are often uncoordinated, frequently coming in late when pests have already been established and caused immense damage. This is worsened by a lack of collective laws (legislation) and principles of action (policies) governing the response to invasion. The coordinated responses in the USA and Italy when *B. dorsalis* was caught in monitoring traps are commendable (Nugnes et al. 2018; Steck et al. 2019). Such rapid responses are missing in SSA, yet projections are that more invasive species are headed to Africa mainly because of climate change and the inability of governments to cope (Sokona and Denton 2001). There is a greater need for political will to unlock economic, financial, and institutional commitment towards managing climate change and invasive species. Most invasive insect pests flourish and spread owing to a lack of public awareness to report such to regulatory bodies. In some cases existing legislation is largely colonial and outdated. This coupled with a lack of adequate coordination between and among government arms, leads to total disaster.

All countries are governed by the Convention on Biological Diversity which came into effect in 1992 (United Nations 1992). The convention clearly states that signatories actively prevent at the onset the introduction of invasive species, but in cases where the pest is already established, thrive to reasonably control or eradicate the said pest. The Global strategy for addressing the problem of invasive alien species (Mcneely 2000) contains all instruments which deal with invasives in one way or the other, but most of them are products of the top-down approach hence not implemented in SSA. Recently, a strategy for managing invasive species was developed to effectively address the issue of invasive species in SSA (Nampala 2020). The strategy recognizes that responses to invasives species are currently reactive, lacking a proactive coordinated approach partly due to poor institutional structures, communication, data sharing, and poor policy implementation.

For Africa to achieve sustainable development goals (SDGs), Agenda 2063, and various national, regional, and international initiatives, particularly in the areas of food and nutritional security, there is a need to address

the enormous threat posed by invasive species. Coordinated strategies will ultimately rally SSA in the area of preventing, excluding, detecting, and managing invasive pests before they impact productivity (Nampala 2020). It remains to be seen whether the African Union (AU), as an administrative body and the member states will live up to expectations and provide required financial, administrative, and regulatory support as envisaged in the strategy.

## Strengths, challenges, and prospects

The human population in SSA is growing at an alarming rate, with 1 billion of the 7.8 billion people in the world currently resident in SSA. Projections place the population of SSA at 3 billion by the year 2100 (Vollset et al. 2020). On one side this is positive considering the human and natural resource base, with potential for social and economic growth in the global village. However, food demand coupled with biophysical, socioeconomic, and policy and regulation issues may erode the gains of human resource capacitation (Bodirsky et al. 2015; Ehui and Pender 2005). Agricultural production has appreciated over the years but has not been met with a corresponding productivity increase (Ehui and Pender 2005).

Management of invasive insect pests is currently largely uncoordinated and lacking political will. Africa is prone to civil war and mismanagement of state resources and aid, as well as a clear disconnect between the ruling elite and the masses (Collier and Hoeffler 2002; Maipose 2000). This has often left most countries without clear systems and resources to deal with livelihood issues. Brilliant policies are often developed but never implemented due to a lack of resources. Strategies such as the recently developed Strategy for Managing Invasive Species in Africa 2021–2030 will require solid commitment from governments to bear fruit (Nampala 2020). Considering that the current allocation to research and development activities by African countries is less than 0.5% of the continent's GDP. Stiff penalties can be introduced to deter African governments from absconding from their duties. A step further towards non-punitive approaches can be introduced through educative forums considering that most Presidents and their Ministers are mostly not scientists and may not understand the full implication of invasive insect pests.

Most pests are intercepted at ports of entry as larvae or their effects observed as plant or fruit damage at the farm level. Rapid diagnostic tools are therefore required if immediate decisions are to be taken. Most immature stages of insects look alike and there are few morphological diagnostic characteristics for consistent identification. There is a need for quick and accurate molecular tools

such as DNA metabarcoding, DNA barcoding, droplet digital PCR among many others (Piper et al. 2019).

Bio-surveillance systems are also integral in the early detection and deployment of prompt intervention strategies (Roe et al. 2004). This is critical for governments in global biosecurity (Boykin et al. 2012). Unfortunately, these are poorly developed in SSA as they lack institutional support. The use of entomopathogens requires in-depth research as different species of pathogens require specific requirements at the production or application stage (Charnley and Collins 2007). Formulation, packaging, and application have to consider various ecological and environmental factors to ensure usability and efficacy (Jackson et al. 2010). Hundreds of entomopathogens have been isolated and evaluated mostly under laboratory conditions and field efficacy data are lacking. The respective pathogens have not been commercialized despite the astounding efficacious results.

Pest management initiatives that advocate for areawide and regional management of invasive species are conspicuously absent in SSA. There has been recent advocacy for Area-Wide Integrated Pest Management (AW-IPM) particularly in high-income countries in the west, as opposed to isolated activities at the farm level (Hendrichs et al. 2007). The success of pest management hinges on buy-in from the stakeholders particularly the growers. The initial implementation of SIT in South Africa was mostly top-down, and farmers slackened in the area of field sanitation leading to mixed successes of the program (Barnes and Eyles 2000; Barnes 2007, 2016). The current SIT campaign against *T. leucotreta* has shown the benefits of stakeholders' buy-in and involvement of growers at all stages (Boersma 2021). Hendrichs et al. (2007) advocate for a program managed from the top, but with a strong presence of stakeholders at the bottom or simply a wholly bottom-up management approach.

Recently coordinated efforts by the Agricultural Research Council (ARC) of South Africa through the Project F3 Fruit Fly Free with funds from Standards and Trade Development Facility (STDF) to establish Pest Free Areas (PFAs) and Areas of Low Pest Prevalence (ALPPs) for regulated fruit fly pests of economic importance in South Africa and Mozambique may not necessarily yield expected results. This is primarily due to the position of South Africa which may be considered the economic hub of Southern Africa. Locking out countries such as Zimbabwe, Zambia, Malawi may spell doom to the Project F3 Fruit Fly Free since fruit flies are transboundary pests and phytosanitary regulations are weak ant points of entry and exit into South Africa thus re-infestations cannot be ruled out.

Nearly adequate management options for most pests now established in SSA have been developed and tested.

For example, most Fruit flies IPM options are highly effective (Midingoyi et al. 2019). Despite the basket of options, many technologies are either not known to farmers or are not implemented (poor adoption). Rigorous awareness and participatory technology dissemination are required to create evidence-based adoption and adaption. Classical biological control is one of the most sustainable, not requiring continuous input from growers once the natural enemies are established. Thus there is a need to build capacities for national governments in terms of skill and infrastructure to allow them to take overproduction and release of natural enemies beyond donor-funded projects which normally end after 3–5 years of funding. When resources are mobilized, relevant government departments can carry over as part of project sustainability.

## Conclusions

We have tried to stay away from the debate on invasion terminologies and ideological differences about invasive insect pests. We have concentrated on what a pest does than its origin and explored the concept of native invasive species and alien invasive species based on the ten insect pests causing enormous losses in SSA. Both the biogeographic and the ecological perspective of invasion provide key elements of the invasion when combined holistically. The convergence is on incursion, encroachment, and spread, irrespective of the origin being native or alien. Today we live in a global village, and transboundary insect pests are wrecking-havoc unchecked. Due to the lack of systems and capacity to detect and ultimately manage invasive pests in SSA, the fruit tree industry has been decimated by *B. dorsalis*, *B. zonata*, *D. citri*, *P. marginatus*, *R. invadens*, *R. iceryoides*, *T. leucotreta*, *P. wayi*, *P. devastans* and *T. erytreae* albeit at various magnitudes. Management options for these pests are numerous but adoption and adaption still lag. Concerted efforts are required to further available knowledge through research, build awareness among stakeholders and embark on Area-Wide- Integrated Pest Management. Harmonization and standardization of management technologies may benefit farmers in terms of saving time and cost as some options apply to more than one pest in the same agro-system.

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#### Availability of and materials

All data are contained within the manuscript.

#### Declarations

#### Ethics approval and consent to participate

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