Challenges to planted forest health in developing economies

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A number of strategies have been proposed to manage the increasing threat of insect pests to non-native plantation forests, but the implementation of these strategies can be especially challenging in developing economies, such as in countries of sub-Saharan Africa. As in other parts of the world, invasions of non-native insect pests in this region are increasing due to increased trade as well as inadequate quarantine regulations and implementation. Some of these invasions result in substantial socio-economic and environmental losses. In addition, new host associations of native insects on the non-native tree hosts continue to occur. Identification of these insect pests is becoming increasingly difficult due to declining taxonomic expertise, and a lack of resources and research capacity hinders the widespread and effective deployment of resistant trees and biological control agents. The necessity to engage with an extremely diverse stakeholder community also complicates implementing management strategies. We propose that a regional strategy is needed for developing regions such as sub-Saharan Africa, where limited resources can be optimized and shared risks managed collectively. This strategy should look beyond the standard recommendations and include the development of an inter-regional phytosanitary agency, exploiting new technologies to identify insect pests, and the use of "citizen science" projects. Local capacity is also needed to develop and test trees for pest tolerance and to deploy biological control agents. Ideally, research and capacity development should, at least initially, be concentrated in centres of excellence to reduce costs and optimize efforts.

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Introduction

By 2050 the world population is expected to reach 9.7 billion, with most of this growth in developing countries, especially Africa (UNDESA 2015; Vira et al. 2015). This will place huge demands on food security, but also on fibre that will be needed for fuel, timber, and various other high end uses. Of further concern is the decrease in total forest area (planted and natural), from 4.28 bil. ha in 1990 to 3.99 bil. ha in 2015 (Payn et al. 2015). However, planted forests are rapidly expanding to meet the demands, with over 110 million ha planted since 1990 (FAO 2015). Planted forests currently account for 7 % of the world's forest area. In many cases, these planted forests consist of non-native species that have been planted due to their rapid growth, favourable properties for timber and other uses such as fuel, paper and cellulose, as well as protection from soil erosion and flooding (Turnbull 1999; Payn et al. 2015). An apt example of non-native plantations are those of *Eucalyptus* species, where plantations of these trees alone increased by 14 million ha from 1985 to 2008. Much of this growth has been in developing economies, particularly India, Brazil and China (Brockerhoff et al. 2013; Hurley et al. 2016).

Despite their recent expansion, the opportunity for planted forests to meet growing demand is seriously threatened by losses incurred from insect pests and diseases. This is largely due to the rapid increase in the introduction of invasive species that become pests of forest trees (Wingfield et al. 2008; Liebhold et al. 2012; Hurley et al. 2016), and the increase in new host associations between herbivorous or pathogenic species and non-native tree hosts (Paine et al. 2011; Wingfield et al. 2011). Some of these species become serious pests that result in severe economic losses, and in some cases threaten the sustainability of plantation species. An example is the Sirex woodwasp, *Sirex noctilio*, a wood-boring hymenopteran native to Eurasia, which together with a fungal symbiont, *Amylostereum areolatum*, infests and kills pine trees (Talbot 1977). Since it was first detected outside its native range in New Zealand around 1900 (Miller and Clark 1935), it has spread to most major pine growing regions of the world (Slippers et al. 2015). Losses from this wasp have been particularly severe in the southern hemisphere, and have necessitated substantial investment in management programs (Hurley et al. 2007; Slippers et al. 2015).

A number of recent reviews have discussed and suggested responses to the increasing threat posed by insect pests and diseases of planted forests (Garnas et al. 2012; Liebhold 2012; Wingfield et al. 2013; Wingfied et al. 2015; Ramsfield et al. 2016). These responses include technological advances in diagnostics, traditional breeding for disease resistance and genetic engineering. They also stress the importance of increased global networks and collaboration in fields such as biological control, pathway risk management and the development of surveillance tools. The application of these recommendations will, however, require considerable effort and resources. This is especially true in the case of developing economies, where plantation development is most intense, but where there are considerable and unique challenges for the implementations of appropriate management strategies.

Sub-Saharan Africa (forthwith referred to as Africa) represents a region where limitations in the ability to respond to pest and disease threats can hinder efforts to increase plantation forestry. Plantation forestry using non-native species has a long history in some countries in this region, including Kenya, South Africa and Zimbabwe (Olivier 2010). The main non-native forest plantation species are *Pinus* (pine), *Eucalyptus* (eucalypts), *Tectona* (teak), and *Acacia mearnsii* (black wattle), with others including *Gmelina* (gamhar) and *Hevea* (rubberwood) (Nair 2001).

As a whole the area covered by plantation forests in Africa is substantially less than in Asia and South America. Total planted forest area in 2015 was 91.8 mil. ha in East Asia, 15 mil. ha in South America and 4.6 mil. ha in east and southern Africa (Payn et al. 2015). But a growing local demand has led to recent investments to establish large plantation areas in this region, including in Ghana, Malawi, Mozambique and Uganda (FAO 2015). The recent dramatic rise in the number of insect pests and diseases of these non-native trees worldwide, including in Africa, however, has highlighted the vulnerability of sustainable plantation forestry in this region (Wingfield et al. 2008; Wingfield et al. 2011; Hurley et al. 2016). It has also raised the level of urgency to develop viable responses within an environment where many of the affected countries lack human capacity, appropriate infrastructure, research support or the means to effectively deploy pest management options.

In this review we consider the health of non-native trees in plantations in sub-Saharan Africa as an example of the challenges faced in many developing economies. We highlight pertinent issues relating to the future success or failure of non-native plantation forestry in such economies. The focus is on insect pests of the main non-native trees being deployed for plantation development in Africa, including the invasive and native pest species. Challenges faced in implementing management strategies, including the initial barrier of identifying the pest species, difficulties in adopting alternative pest management strategies, and problems relating to engaging with a complex stakeholder community, are discussed. We identify opportunities to enable the application of pest management approaches that should address at least some of the issues in the context of developing economies.

The invaders

Africa has been the recipient of numerous non-native insects that have become pests in plantations. This is despite the small area planted to non-native tree species compared with many other regions (FAO 2010). For example, *Eucalyptus* plantations as non-native species are predominantly in Asia and South America (Iglesias-Trabado and Wilstermann 2008; Hurley et al. 2016). Interestingly, established non-native insect pests have been mainly reported on *Pinus* and *Eucalyptus* species (Table 1). Non-native insects have not been reported on *Acacia mearnsii*, other than those introduced for the biological control of this tree such as the gall midge *Dasinerua rubiformis* and the seed-feeding weevil, *Melanterius maculatus* (Impson et al. 2008). Only one non-native insect pest has been reported on *T. grandis*, namely the teak defoliator, *Hyblaea puera* (Nair 2001). This is despite the presence of many serious insect pests on both black wattle and teak in their native ranges (Searle 1997; Nair 2001; Sharma et al. 2013; McTaggart et al. 2015). The difference in area planted to the host species may contribute to this pattern. For example, in South Africa only 7.2 % of forest plantations were planted to *A. mearnsii* in 2013, compared to 41.7% planted to *Eucalyptus* spp. and 50.8 % planted to *Pinus* spp. (www.forestry.co.za , 'Abstract of South African Forestry Facts 2012-2013, accessed 20 March 2016). This is in contrast to fungal pathogens, where a number of non-native pathogens of pine, eucalypts, as

Table 1. Non-native insect species reported as pests in plantations of *Acacia mearnsii*, *Eucalyptus* spp., *Pinus* spp. and *Tectona grandis* in sub-Saharan Africa. Sources: Nair (2001), Roux et al. (2012) and Bush et al. (2016). Grey blocks indicate that the insect has been reported in that country and black blocks indicate the country where it was first reported in the region (when known).

				Country**					
			Host	**K**	**Ma**	**SA**	**U**	**Za**	**Zi**
Blastopyslla occidentalis	Eucalyptus psyllid	*Psyllidae*	E			■			
Cinara cronartii	Black pine aphid	*Aphididae*	E	□		■			□
Ctenarytaina eucalypti	Bluegum psyllid	*Psyllidae*	E	□		■			
Eulachnus rileyi	Pine needle aphid	*Aphididae*	P	□	□	■	□	□	■
Glycaspis brimblecombei	Redgum lerp psyllid	*Psyllidae*	E	□	□	■	□	□	□
Gonipterus sp.2	Eucalyptus snout beetle	*Curculionidae*	E		□	■			□
Hyblaea puera	Teak defoliator	*Hyblaeidae*	T		□	□	□		
Hylastes angustatus	Pine bark beetle	*Curculionidae*	P			■			□
Hylurgus ligniperda	Red-haired pine bark beetle	*Curculionidae*	P			■			□
Leptocybe invasa	Bluegum chalcid	*Eulophidae*	E	■	□	□	□	□	□
Ophelimus maskelli	Eucalyptus gall wasp	*Eulophidae*	E			■			
Orthotomicus erosus	Mediterranean pine engraver beetle	*Curculionidae*	P			■			
Phoracantha spp.	Eucalyptus longhorn beetles	*Cerambyciddae*	E			■		□	□
Pineus boerneri	Pine woolly adelgid	*Adelgidae*	P	■	□	□			□
Pissodes sp.	Pine weevil	*Curculionidae*	P			■			
Sirex noctilio	Sirex woodwasp	*Siricidae*	P			■			
Spondyliaspis c.f. plicatuloides	Shell lerp psyllid	*Psyllidae*	E			■			
Thaumastocoris peregrinus	Bronze bug	*Thaumastocoridae*	E	□	□	■	□		□
Trachymela tincticollis	Eucalyptus tortoise beetle	*Coccinelidae*	E			■			

*E= *Eucalyptus*, P=*Pinus*, T=*Tectona*

**K=Kenya, Ma=Malawi, SA=South Africa, U=Uganda, Za=Zambia, Zi=Zimbabwe well as black wattle and teak, have been reported in Africa (Wingfied et al. 2001; Wingfield et al. 2011; Mamle and Roux 2015; McTaggart et al. 2015)..

The intra-regional spread of non-native insect pests of plantation trees in Africa is generally poorly documented. However, with regard to insect pests of pine and eucalypts, it is clear that South Africa is a major port of entry of these species into the region (Table 1, Faulkner et al. (2017)). Of the 18 introduced insect pests, only two were not first reported in South Africa; the pine woolly adelgid, *Pineus boerneri*, was first reported in Kenya in 1969, and subsequently detected in South Africa (1978), Zimbabwe (1980) and Malawi (1984), and the blue gum chalcid, *Leptocybe invasa*, was first detected outside its native range in Israel in 2000 (Mendel et al. 2004) and subsequently reported in Kenya and Uganda in 2012 and then in various other African countries (Nyeko et al. 2009; Dittrich-Schröder et al. 2012). This pattern is in contrast to invasive bird species, where South Africa is a major recipient of invasive birds from other African countries. This is possibly because the intentional introduction of most of these birds is less likely to reflect trends in the direction of trade (from South Africa to other countries in the region), as would be the case for accidentally introduced insect pests (Faulkner et al. 2017).

The reported intra-regional spread of introduced non-native insects in Africa, where South Africa is observed to be the main donor, could also be influenced by differences in survey intensity. South Africa hosts the Tree Protection Cooperative Programme (www.fabinet.up.ac.za/tpcp; accessed 24 August 2016), a 28-year-old research initiative that involves the University of Pretoria, private forestry companies and the government, which includes extension services and an established communication network facilitating new pest and disease reporting. It is likely that pest surveys and reporting efficiency is lower in countries where similar initiatives or capacities have not been established.

The above-mentioned patterns raise the expectation that non-native insect pests of plantation trees will continue to be introduced into Africa. In fact, Africa could be expected to receive a greater proportion of future introductions compared to some other regions. Santini et al. (2013) reported that the further spread of invasive forest pathogens is expected to occur in countries that have experienced isolation in the past. The same trend is likely to be observed with insect pests. This will be especially true in regions that are experiencing a rapid increase in their international trade. In Africa, much of this increase in trade is suspected to be the result of increasing trade partnerships between African countries and Asia. For example, the share of total imports from China to Sub-Saharan Africa increased from 1.95 % in 1995 to 16.54 % in 2015 (www.wits.worldtrader.org, accessed 20 March 2017).

The increase in trade, associated with a lack of effective implementation of phytosanitary regulations relating to quarantine and enforcement of policies will likely contribute to an increase in the introduction of non-native species in Africa. Although insect pests can be introduced on a number of different commodities, ranging from used vehicles to the clothing of tourists (Ridley et al. 2000; Withers 2001), two of the most likely commodities on which forest insect pests can be moved are untreated wood products and live plant material (Brockerhoff et al. 2006; Haack 2006; Kenis et al. 2007; Roques et al. 2009; Skarpaas and Økland 2009; Liebhold et al. 2012). A phytosanitary standard, ISPM 15 (International Standards for Phytosanitary Measures No. 15) has been established and has been reported to provide net benefits in reducing costs from the introduction of non-natives (Leung et al. 2014). However, implementation of this standard has been a problem in many African countries. In 2012, international standards for phytosanitary measures for plants for planting were adopted by member countries, but implementation of this guideline by countries in Africa has been slow. Furthermore, in many African countries, general phytosanitary requirements include applications for the import of plants for planting, and the inspection of those commodities before export and on arrival. But, there are reports of eucalypt plants from Asia and South America being imported for planting in African countries (H. O. Kojwang, pers. comm.). This raises serious doubts as to whether the recommended phytosanitary measures are being uniformly enforced.

Data regarding the social and economic impact of non-native insect pests of plantations in Africa is generally lacking. For cases where data are available, the heavy impact of these introductions is very evident. For example, the Sirex woodwasp, *Sirex noctilio*, was first detected in South Africa in 1994 (Tribe 1995) and by 2010 it had become established throughout the country and was considered the most serious pest of pine causing an estimated loss of ZAR300 million (approx. US$24 million, based on exchange rate on 20 March 2017, of US$1 = ZAR12.69) per annum (Hurley et al. 2007). This insect has not yet been reported in African countries other than in South Africa and Swaziland, but will likely seriously threaten the sustainability of pine forestry in the region when it does spread further. Another example is the millions of US$ reported to be lost annually due to infestations of aphids on pines and cypress in east and southern Africa (Murphy 1996).

Two recent examples of serious economic losses caused by non-native insects are those involving *Leptocybe invasa* and *Glycaspis brimblecombei*. These insects, first detected in Africa in 2002 and 2012, respectively, are both pests of eucalypt trees in their invaded range. *Leptocybe invasa* causes galls on the stems, petioles and leaves resulting in early leaf senescence and malformation, and *G. brimblecombei* is a sap-sucking lerp psyllid. Heavy infestations of these insect pests can result in stunted growth of the trees and in severe cases tree death. In the case of *L. invasa*, tree mortality can be particularly high in nurseries and in recent plantings. Both insect pests are now widespread on the continent (Table 1), with the extent of damage so high in some areas that it threatens to halt eucalypt plantation development (BPH, personal observation). For example, in Zimbabwe, a programme has been launched to plant large areas with eucalypts in an effort to save the native woodlands that are currently being depleted due to their use as a source of fuel for the curing of tobacco leaves (http://www.herald.co.zw/tobacco-curing-woodlots-the-answer, accessed October 2016). However, infestations by *L. invasa* have severely affected the uptake of this initiative by local farmers, threatening its success and potentially resulting in severe environmental and economic losses if the pest is not managed effectively.

The threat of native pests

The relatively new development of plantation forests in parts of Africa and the great diversity of native insects is likely to result in numerous new incidents of native insect pests infesting these exotic trees. There are already many native insects recorded as pests of plantation trees in Africa (Table

Table 2. Native insect species reported as pests in plantations of *Acacia mearnsii*, *Eucalyptus* spp., *Pinus* spp. and *Tectona grandis* in sub-Saharan Africa. As pest occurrences are not always reported and reports not always published, this list is not exhaustive, but provides an example of the diversity of native insects reported as pests on these trees. Sources: Nair (2001); Schabel (2006); Wagner et al. (2008); Roux et al. (2012)

Species	**Family**	**Order**	**Feeding guild**	**Tree species**	**Country reported**
Achaea lienardi	Erebidae	Lepidoptera	Defoliator	Am	South Africa
Agrotis spp.	Noctuidae	Lepidoptera	Establishment pest	Am, E, P	South Africa
Anaemerus tomentosus	Curculionidae	Coleoptera	Wood borer	E	Ghana
Analeptes trifasciata	Bostrychidae	Coleoptera	Wood borer	E, Tg	Ghana
Apate monachus	Bostrychidae	Coleoptera	Wood borer	Tg	Ghana
Apate terebrans	Bostrychidae	Coleoptera	Wood borer	E, Tg	Ghana
Ascotis selenaria reciprocaria	Geometridae	Lepidoptera	Defoliator	E, Tg	Nigeria, Ghana
Buzura sp.	Geometridae	Lepidoptera	Defoliator	E	Southern Africa
Chaetastus tuberculatus	Platypodidae	Coleoptera	Wood borer	E	Ghana
Chaliopsis junodi	Psychidae	Lepidoptera	Defoliator	Am	South Africa
Cleora herbuloti	Geometridae	Lepidoptera	Defoliator	E, P	South Africa
Colasposoma spp.	Chrysomelidae	Coleoptera	Defoliator and shoot feeder	Am, E, P	South Africa
Coryphodema tristis	Cossidae	Lepidoptera	Wood borer	E	South Africa
Diacrisia infestigatorum	Arctiidae	Lepidoptera	Defoliator	Tg	Ghana
Diacrisia lutescens	Arctiidae	Lepidoptera	Defoliator	E	Ghana
Doliopygus conradti	Platypodidae	Coleoptera	Wood borer	E	Ghana
Doliopygus erichzoni	Platypodidae	Coleoptera	Wood borer	Tg	Ghana
Ellimenistes laesicollis	Curculionidae	Coleoptera	Defoliator and establishment pest	E	South Africa
Euproctis fasciata	Lymantriidae	Lepidoptera	Defoliator	E	Ghana
Euproctis terminalis	Lymantriidae	Lepidoptera	Defoliator	Am, E, P	South Africa,
Gonometa podocarpi	Lasiocampidae	Lepidoptera	Defoliator	E, P	Kenya, Tanzania, Uganda
Gynanisa maia	Saturniidae	Lepidoptera	Defoliator	Am	South Africa
Helopeltis anacardii	Miridae	Hemiptera	Sap-sucker	E	Malawi
Holocerina smilax	Satruniidae	Lepidoptera	Defoliator	P	South Africa
Hypopholis sommerii	Scarabeidae	Coleoptera	Defoliator	Am, E, P	South Africa
Hypothenemus eroditus	Curculionidae	Coleoptera	Wood borer	Tg	Ghana

Hypothenemus pusillus	Scolytidae	Coleoptera	Wood borer	Tg	Ghana
Hypsipyla robusta	Pyralidae	Lepidoptera	Shoot borer	Tg	Widespread
Imbrasia cytherea	Saturniidae	Lepidoptera	Defoliator	Am, E, P	South Africa
Imbrasia tyrrhea	Saturniidae	Lepidoptera	Defoliator	Am, E, P	South Africa
Lygidolon laevigatum	Miridae	Hemiptera	Sap-sucker	Am	South Africa
Macrotermes spp.	Termitidae	Isoptera	Establishment pest	Am, E	Widespread
Manowia sp.	Eumastacidae	Orthoptera	Defoliator	P	Malawi
Monochelus calcaratus	Scarabeidae	Coleoptera	Defoliator	Am	South Africa
Narosa viridana	Limacodidae	Lepidoptera	Defoliator	E	Zambia
Neocleosa sp.	Geometridae	Lepidoptera	Defoliator	E	Southern Africa
Orgyia basali	Lymantriidae	Lepidoptera	Defoliator	E, Tg	Nigeria, Ghana
Pachypasa capensis	Lasiocampidae	Lepidoptera	Defoliator	Am, E, P	South Africa
Parasaissetia nigra	Coccidae	Hemiptera	Sap-sucker	E	Ghana
Phymateus kazschi	Acrididae	Orthoptera	Defoliator	E	Nigeria, Ghana
Planococcoides njalensis	Coccidae	Hemiptera	Sap-sucker	Tg	Ghana
Platypus lintzi	Platypodidae	Coleoptera	Wood borer	E	Ghana
Pseudobunaea irius	Saturniidae	Lepidoptera	Defoliator	Am, E, P	South Africa
Saissetia coffease	Coccidae	Hemiptera	Sap-sucker	E	Ghana
Strepsicrathes rhothia	Tortricidae	Lepidoptera	Defoliator	E	Ghana
Various	Scarabeidae	Coleoptera	Establishment pest	Am, E, P	Widespread
Xanthisthisa tarsispina	Geometridae	Lepidoptera	Defoliator	P	Malawi
Xyleborus perforans	Curculionidae	Coleoptera	Wood borer	E	Ghana

2). These include many leaf-defoliating insects, predominantly the immature stages of lepidopterans, as well as wood- and shoot-boring insects; mainly beetles, although also including lepidopteran species such as *Coryphodema tristis* and *Hypsipyla robusta*. There are also a number of sap-sucking hemipterans and various insects that attack newly planted trees (pests of establishment).

Native insect pest species are present on all the main non-native plantation tree hosts considered here, namely *Pinus* spp., *Eucalyptus* spp., *A. mearnsii* and *T. grandis* (Table 2). According to Branco et al. (2015), a greater number of native pests would be expected on native trees that are more widely planted and where closer congeneric tree species are present. Based on this view, *A. mearnsii* would be expected to harbour the greatest number of native species due to the numerous species of native *Vachellia* and *Senegalia* spp., both formerly *Acacia*. This would be followed by *Eucalyptus* spp. and *T. grandis*, due to the presence of numerous native species in the same families, namely Myrtaceae and Lamiaceae. *Pinus* spp. would be expected to be the least colonized by native species as there are no native Pinaceae in sub-Saharan Africa. Data on the number of native insects in Africa that colonize these non-native tree hosts is not sufficient to make comparisons between the trees. However, there appear to be no clear differences in the number of pest species reported on the different non-native tree hosts (Table 2). Olivier-Espejel (2016) reported a high number of native insects colonizing *A. mearnsii* in South Africa, but very few of these are considered pests. The determinants of native insect pest species on these non-native hosts could be due to ecological factors such as a mass effect, where the number of native species could be influenced by the proximity to large source populations of these insects (Shmida and Wilson 1985).

In some African countries, native pests are dominant and pose a greater threat to plantation forests than introduced invasive species. This is especially true for teak, *T. grandis*, where only *H. purea* is reported as a non-native insect pest in Africa, but where a number of insects native to Africa have adapted to infest these trees (Table 2). Native pest species are also dominant on black wattle, *Acacia mearnsii*. Infestations by the wattle mirid, *Lygidolon laevigatum*, and the wattle bagworm (*Kotochalia junodi*) are considered the most serious insect pests of *A. mearnsii* in South Africa (Roux et al. 2012).

The pest status of native insects varies considerably between tree species, with some often not warranting control measures while others can result in substantial losses. Pests of establishment, such as native white grubs (larvae of scarab beetles) and cutworms (*Agrotis* spp.) for example can result in substantial mortality of newly planted stands (Govender 2007). These insects are especially problematic on first plantings in areas previously covered with natural vegetation. In East Africa, the lepidopteran *Gonometa podocarpi* is a serious defoliator on pines, as well as *A. mearnsii* and certain *Eucalyptus* species (Okelo 1972). The pest status of native species also varies across time, where outbreaks may be seasonal and not observed every year.

The cossid moth, *Coryphodema tristis* (Cossidae, Lepidoptera), represents one of the most dramatic examples of the potential impact of host range expansion in plantation forests. This wood-boring insect is native to South Africa (Degefu et al. 2012), where it has been recorded on a wide range of native hosts and was also previously reported as a pest on quince trees and grape vines (Petty 1917; Kroon 1999). In 2004, *C. tristis* was reported for the first time on the plantation-grown *Eucalyptus* *nitens* (Gebeyehu et al. 2005). Subsequent infestations have resulted in up to 80% infestation of trees at some sites (Boreham 2006), prompting urgent investigations to replace this species or to develop methods to control the pest.

Taxonomic challenges

One of the most serious challenges in response to the threat posed by pests of plantation forest trees in Africa is the difficulty experienced in identifying the pests. In many cases where serious pests are reported, difficulties to obtain a positive and reliable identification of the pest can result in serious delays in management responses. This has been the case for invasive pests such as the bronze bug, *Thaumastocoris peregrinus*, which was originally identified as *T. australicus* (Jacobs and Neser 2005), as well as the *Spondyliaspis* sp. reported in South Africa in 2014 (Bush et al. 2016), where the species identify has yet to be confirmed. In addition, in many cases reports of insect pests are made only in informal literature and without relevant information or access to specimens to allow comparison across studies.

The problem with insect identification is more prevalent with native species. This is due primarily to the large number of possible native pest species and the dwindling taxonomic capacity in the region (even from its low base). In the southern African region alone, past estimates of insect diversity suggested 43 565 known species (Scholtz and Chown 1995), with likely tens, if not hundreds, of thousands of species still not described. Even for those that have been described, information is often scant or difficult to access. Consequently, it must be expected that there will be many emerging pest species that have not been described and where identification problems will frustrate management options.

Misidentification of pest species can result in inappropriate management approaches being implemented. This is particularly relevant in the case of classical biological control, where identification and collection of biocontrol agents in the native range of the pest, or sharing of biocontrol agents between regions, may result in the introduction of ineffective or suboptimal agents. An interesting case here is that of the eucalypt snout beetle, which was first detected in South Africa in 1916 (Tooke 1955) and is now widespread on the continent. This insect was originally described as *G. scutellatus*, and resulted in an extensive survey in Australia to locate and import biocontrol agents. These efforts culminated in the introduction of the egg parasitoid, *Anaphes nitens*, in South Africa and the later introduction of this parasitoid to other countries around the world. However, the recent report of *G. scutellatus* as a species complex including some that remain undescribed, such as *G. scutellatus* sp. 2 in South Africa, has complicated the situation (Mapondera et al. 2012). Thus, different species of *Gonipterus* have moved globally and this has prompted questions regarding the specificity of *A. nitens* and whether it will be necessary to import more specific and potentially more effective natural enemies for the pest.

An inability to recognize multiple cryptic species in a region can also make quarantine and resistance breeding ineffective. For example, Nugnes et al. (2015) recently showed that *L. invasa* has a cryptic sister species that is also spreading around the world. This cryptic second species is common in

South-East Asia, but has now been detected in Ghana and South Africa (Dittrich-Schröder 2014). The impact of this diversity on selection of resistant plant material, which is one of the main control methods for the pest, could be substantial. The fact that the cryptic species was not known for some time also means that quarantine measures could not be effectively implemented.

Capacity for management

Insecticides continue to represent a substantial component of the strategies used to manage insect pests in Africa. This is partly due to the lack of available alternative methods for some insects. It is also especially the case for native insects, where the natural enemy community does not suppress pest populations effectively. Examples here include pests of establishment such as white grubs (larvae of scarab beetles), cutworms (*Agrotis* spp.), termites and numerous defoliating beetles and lepidopteran larvae (Nair 2001; Govender 2007).

Even when alternatives to insecticides are available, there is often no obvious incentive to use a method that may be more costly to implement and / or have a longer effect time. An exception is where the forest products have been developed for an international market with strict certification requirements that prohibit or strongly regulate the use of chemicals. For example, due to the strong export focus of the forestry industry in South Africa, 84% of the plantation area is certified by the Forestry Stewardship Council (https://us.fsc.org/). Consequently, management approaches that provide an alternative to insecticides are funded and implemented in South Africa. However, in many other African countries, the majority of land is planted by small-scale farmers growing trees for local use and there are few incentives to utilise alternative approaches to insecticides (authors, pers. observation). The use of insecticides to manage pests in these countries most likely results in detrimental environmental effects and it increases the probability that the target insects will develop resistance to the insecticide.

Increasing resilience of plantations to reduce damage by pests is best achieved by planting of resistant species or genotypes (Wingfied et al. 2015). Many of the larger plantation companies are investing substantially to develop a large array of clones, with pest and disease resistance becoming an increasingly important criterion for selection (Wingfield et al. 2013). However, development of or access to these resistant genotypes is often not possible for smaller enterprises or farming communities. For example, plantings of *Eucalyptus grandis* x *camuldulensis* clones in Zimbabwe and Kenya is widespread, despite the susceptibility of those particular clones to *L. invasa* (authors, personal observation). Where deployment of resistant clones is not feasible or effective, an effective route is to plant seedling stands of selected families (King and Alfaro 2004; Wingfield et al. 2013). Species replacement may in some cases be the most suitable option, as was the case with infestations of the eucalypt snout beetle, *Gonipterus* sp. 2, in South Africa, which together with the fungal pathogen, *Teratosphaeria nubilosa*, resulted in the replacement of *E. globulus* and *E. viminalis* for less susceptible species (Tooke 1955; Hunter et al. 2008). Mixed species forests have also been shown to be more resistant to infestation by forest insects (Jactel and Brockerhoff 2007; Jactel et al. 2012) and can result in the increased presence and effect of natural enemies (Klapwijk et al. 2016). But this strategy has the disadvantages of growth competition between the species and lack of uniformity that can negatively influence harvesting and other forestry operations.

Classical biological control can be used to effectively manage populations of introduced insect pests in plantations and it has become one of the main management approaches in Africa. This is particularly in South Africa, where biological control agents have been intentionally introduced for eight pest insects (Garnas et al. 2012; Mutitu et al. 2013; Dittrich-Schröder et al. 2014). But concerns regarding possible non-target effects of biological control agents has resulted in stricter regulations for their import (Hajek et al. 2016). The result is that long development periods and associated high levels of investment are required to undertake host specificity tests and other experimentation before a biological control agent can be released. This, together with the need for certified quarantine facilities that are needed for pre-release testing, has restricted the use of classical biological control agents to a small number of countries and institutes on the continent. In addition, sharing biological control agents between countries can be difficult due to bureaucratic hurdles associated with import regulations and requirements to repeat host specificity tests. This can be true even where a biological control agent is being sourced from a neighbouring country and where eventual natural spread is inevitable.

Behavioural control is not commonly used to manage insect pests of plantation trees, but possibilities are currently being explored. Lure-based traps, using pine-volatile lures, have already been used extensively to monitor the spread of *S. noctilio* (Hurley et al. 2012a; Hurley et al. 2015; Sarvary et al. 2015). And recent studies have used the "by-catch" from these traps to identify other potential pest species (Olivier-Espejel et al. 2016). These traps have been used for quantitative monitoring, but ongoing research is considering the possibility of also using traps to manage insect pest populations. In this regard, Bouwer et al. (2015) recently identified the pheromone of the cossid moth *C. tristis*, and research is currently underway to optimize trap spacing and to investigate the effect of mass trapping to reduce populations of this pest. The outcome of this research is of particular importance, given that there are no other available management approaches for this insect, other than species replacement.

Effectively engaging stakeholders

In plantation forestry, as is true with agriculture, the impacts of research findings are largely dependent on the efficacy of engaging with stakeholders to transfer emerging new knowledge. In the case of plantation forestry in Africa the stakeholder community is diverse, ranging from small-scale farmers to large commercial companies. This community is also changing, where, for example, in some countries such as South Africa, the ownership of substantial areas of plantation forest is being transferred to small-scale farmers (M. Peter, pers. communication; http://www.fao.org/forestry/12510-0bf4e5f3c791fcb54e6ff81004ba6c9da.pdf, accessed October 2016). The stakeholder community is further partitioned by a remarkable diversity of ethnic groups and languages, where Africa is home to about 2000 languages with five countries having 100 or more languages (Heine and Nurse 2000).

An important component of engagement with stakeholders in plantation forestry is to understand their perception and awareness regarding pests and diseases (Marzano et al. 2015). Studies to understand these factors are few in number globally and this is especially so in the case of plantation forests in Africa. Two studies that have considered farmers' perceptions to the eucalypt insect pest, *L. invasa*, in Uganda (Nyeko et al. 2007) and Kenya (Mutitu et al. 2007). Both suggest a general lack of knowledge regarding possible control strategies for the pest. Likewise, Hurley et al. (2012b) considered the perceptions and awareness of relevant stakeholders to the pine pest, *S. noctilio.* They found levels of awareness were generally high, which could be attributed to an awareness campaign that had preceded the study. However, levels of awareness were lower for non-first language English speakers, likely because English had been the medium for most of the awareness communications.

Providing "on ground" training to farmers, foresters and other relevant stakeholders on the identification and appropriate management approaches for pests is fundamentally important to a broader pest management programme. When small-scale farmers dominate the forestry community, such initiatives become more challenging. Here, the Technical Cooperation Programmes (TCP) of the Food and Agriculture Organization (FAO) of the United Nations (http://www.fao.org/europe/programmes-and-projects/tcp/en/, accessed July 2016) seek to cooperate with selected governments to assist in this daunting task. TCP projects aimed at providing training and technical support for the management of eucalypt insect pests are currently underway in Zambia, Zimbabwe, Mozambique and Uganda.

Towards a regional strategy

Insufficient capacity to enforce quarantine policies is likely to remain a problem in most developing world countries in the foreseeable future. A possible solution would be the establishment of inter-regional phytosanitary agencies to improve communication between countries regarding trade in high-risk commodities and the pests that might be accidentally moved. This would allow for a focus on preventative measures and also facilitate preparations for likely invasions. Such phytosanitary agencies have been established previously; for example, the SADC (Southern African Development Community) Sanitary and Phytosanitary Protocol of 2008. Involvement of the relevant governments is now required to ensure they remain active and effective.

The development of online tools using DNA-based data (for example for the CO1 barcoding gene) could alleviate shortage of taxonomic expertise in the region. A number of databases already exist that house information about insect pests (e.g. GenBank, www.ncbi.nlm.nih.gov/genbank; QBOL: Quarantine organisms Barcode Of Life, www.qbol.org). Curated datasets from these public data, augmented by ongoing work in real time (ie. not only after publication), that is tailored for regional information needs about current and quarantine pest species, biological control agents and related insects in plantation environments, would be a relatively affordable approach to confirm and compare the identity of samples. Through the curation of such a database, scarce expertise across the continent can be shared.

More extensive and effective surveillance programmes are needed to detect and report the arrival and spread of pests within and between countries. However, such programmes are costly to establish and maintain. For this reason they have generally not been effective in developing economies (Bebber et al. 2014). Established networks such as FISNA (Forestry Invasive Species Network for

Africa) (http://www.fao.org/forestry/fisna/en/, accessed July 2016) could assist in disseminating information on country reports, but they lack the resources for effective monitoring and reporting at a country level.

One possible approach that could enhance monitoring capacity would be the establishment of citizen science programmes (Dickinson et al. 2010). Data obtained from citizen science projects can have relatively high levels of inaccuracy, but when managed well they can result in an overall gain in sampling efficiency (Gardiner et al. 2012). Citizen science projects have already been used in Africa in ecological research and other areas (Hulbert 2016), but the potential use in plantation forest systems has not been fully explored. In the absence of widespread regional capacity and investment, centrally coordinated citizen science projects would significantly increase the network of observers.

Post-establishment management approaches require an increase in local capacity and greater inter-regional collaboration. An increase in local capacity is urgently needed to develop and deploy resistant tree genotypes and species (Wingfield et al. 2013). This alone would contribute substantially to reducing losses from insect pests in many countries, where highly susceptible species are still planted.

Areas such as biological control require development of local capacity for the deployment of biocontrol agents. But research related to the testing and optimization of new agents will likely be confined in a small number of centres. This is because of the cost and technical expertise to maintain quarantine facilities, equipment and technical expertise to work with previously unstudied insects, and the networks and costs associated with collecting biocontrol agents. Such centres would benefit from association with the Biological Control of Eucalyptus Pests (BiCEP, bicep.net.au) that has been developed between industries and research groups in Australia, Brazil and South Africa. Besides research on classical biological control agents, these centres should focus on opportunities for mass rearing and augmentative releases of biocontrol agents. Furthermore, there is currently virtually no focus on conservation biological methods to enhance effectiveness of native and introduced natural enemies. Both these approaches present an opportunity to increase the use and efficacy of biological control of insect pests of non-native plantation species in sub-Saharan Africa.

Conclusions

The threat posed by insect pests of plantation trees in Africa is increasing. If it is not addressed, the future of plantation forestry in many, if not most of the region, will be compromised. Increasing global trade, limitations of quarantine measures and climate change, imply that greater numbers of alien species must be expected and some of them will become serious pests. In addition, new associations between native insects and introduced trees will continue to emerge. In most cases, the species involved and their biology will be unknown and this will delay the implementation of appropriate responses.

It is clear that the threats posed by insect pests and diseases to non-native plantation forestry in Africa are substantial. Governments, communities, private companies and investors in this region that don’t adequately support research and extension capacity in tree health will do so to their own detriment. Even with investment from individual governments and other stakeholders, the regular arrival of new pests will place strain on available resources. Consequently, we believe that together with building local capacity, development of centres of excellence in the region and connecting these effectively will be critical to ensuring the sustainability and growth of non-native plantation forestry in Africa.

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