Pesticidal Plants for Stored Product Pests on Small-holder Farms in Africa

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Abstract

Despite the near elimination of pests from food stores in industrialised nations, insects are still the most important challenge to food security for small-holder farmers in less developed nations. Losses are frequently as high as 20 %. Synthetic products provide effective control when used correctly but are not sustainable or universally appropriate and present many challenges for farmers, not least of all their cost. Pesticidal plants offer an economic, effective and often the only alternative. Much published research, however, overlooks critical knowledge gaps providing outputs that are unlikely to improve pesticidal plant use or improve food security. This chapter identifies opportunities for better targeted research and improvements for uptake and use of pesticidal plants. We also highlight how a deeper understanding of different morphs, gender and age of insect can influence experimental results and should be considered more carefully.

To be effective plant materials need to show low animal and environmental toxicity at typical application levels but at the same time be effective against a wide range of target species, at low doses and with longevity. They must also be low cost, safe, compatible with other pest management technologies and stable and have no consequences for the stored products such as impairing flavour. Research should be targeted at optimising the efficacy of the pesticidal plants already known to have potential, and this should be supported by chemistry to fully understand spatial, temporal and phenotypic variability and nontarget impacts. Availability of plants is a

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limiting factor to uptake so propagation and cultivation of elite provenances would alleviate pressure on natural ecosystems and improve reliability of efficacy and supply when supported by improved harvesting techniques. The large-scale commercialisation of plants may not compete with synthetic products globally but local production may foster a mechanism to support and encourage uptake through local markets and value chains.

1 Introduction

In recent decades, the postharvest sector for durable crops (grains and legumes) has undergone a massive divergence between developed and developing economies. Relatively advanced large-scale technologies such as refrigerated silos, fumigation and controlled atmosphere storage have virtually eliminated the problems of insect attack after harvest across Europe, North America and Australia. However, the situation in developing countries could not be more different. Particularly in the Tropics and for the relatively smaller-scale crop production systems found in sub-Saharan Africa and South Asia, postharvest losses routinely result in 10–20 % of food produced being lost along the value chain after harvest. In countries where subsistence and small-scale farmers dominate, postharvest losses from insects mean that farmers are often obliged to sell their crops soon after harvest because they do not have access to affordable technology that will protect their stored crops at the small-scale level. For subsistence farmers, the rapid deterioration caused by storage insects can mean seasonally extended food insecurity, lower quality and nutritive content of their produce and the need to account for loss expectations by expanding the amount of land cultivated. Some of the best estimates of postharvest loss that include small-holder production are now being collected in southeastern Africa with data made available by the African Postharvest Losses Information

System (APHLIS).[1] This interactive map and database show postharvest losses can vary across seasons, regions and commodity type and gives some indication of how severe postharvest losses can be for subsistence farmers, e.g. during 2007 losses were up to 35 % for maize in most of Zimbabwe, while up to 25 % for most of Mozambique, Tanzania and eastern Kenya (see Fig. 9.1).

Although many initiatives are trying to develop and distribute appropriate technology for on-farm storage, e.g. hermetically sealed bags, insect-proof containers, etc., most subsistence farmers continue to store produce in woven polythene sacks or indigenously designed granaries. As subsistence farmers are, by definition, poor in resources and constitute some of the most marginalised people globally, providing them with new technology is fraught with difficulty to overcome vested interests in maintaining the status quo (e.g. market traders, pesticide manufacturers) as well as convincing and enabling farmers to invest in storage technology. Typically, most subsistence farmers do nothing to prevent postharvest losses. Their experience tells them to sell their produce early to avoid losses because they cannot maintain grain quality later in the season when market prices are high for good-quality grain. If farmers do plan on storing longer than 3 months, they usually treat their grain with a commercially available synthetic pesticide, particularly if they hope to sell the grain.

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[1] http://www.aphlis.net

PHL values 2007

- ☐ < 5 %
- ☐ 5 - 10 %
- ☐ 10 - 15 %
- ☐ 15 - 20 %
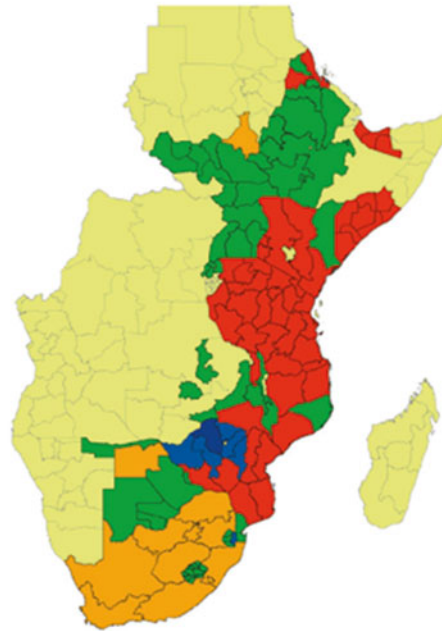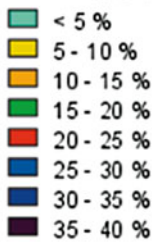- ☐ 20 - 25 %
- ☐ 25 - 30 %
- ☐ 30 - 35 %
- ☐ 35 - 40 %

Fig. 9.1 Postharvest losses (PHL) for maize collected at the provincial level across southeastern African states during 2007 (Data derived from http://www.aphlis.net)

The most abundant pesticide used in sub-Saharan Africa to control insects in grain storage is the fumigant phosphine, which can really only be effectively employed at large scale as it requires gas-impermeable sheeting and monitoring equipment, the costs of which are beyond the reach of small-holder farmers. In some countries, farmers can legally (or illegally) obtain phosphine and attempt to fumigate their grain themselves at home but through poor knowledge do not maintain a gas-tight environment, often leading to human poisoning. For small-holders Actellic (pirimiphos) dust or its sister product Actellic Super (pirimiphos-methyl and permethrin) dust is used most commonly (Obeng-Ofori 2010). These are typically highly effective when used correctly but distribution may be restricted in some rural areas, and perhaps the most difficult problem with Actellic, as with most other pesticides, is that they are frequently adulterated by unscrupulous traders or poorly stored/expired

product is used. Inappropriate application, the development of resistance among insect species and the limited number of insecticides available in remote areas are just some of the problems facing small-scale use of insecticides for stored production protection. Insecticides are typically applied without adhering to manufacturer advice about safe handling, and this can place farm workers, often women and children, at risk. In addition, the safety of food for consumers is not a high priority, and there is no mechanism for assessing chronic/acute outcomes from exposure. In 2013, 23 children died in an Indian school after eating a meal contaminated by pesticide.[2] Pesticide dumping and the impact on wildlife and beneficial organisms are also serious, while the prohibitive cost of pesticides for poor farmers can be a strong disincentive to use them. Recent surveys highlight these issues and report that the

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[2] http://www.bbc.co.uk/news/world-asia-india-23436348

problems are well understood by farmers (Kamanula et al. 2011; Nyirenda et al. 2011) and have led to farmers simply avoiding synthetic pesticides altogether but at the cost of stored food losses.

Storage losses can be avoided using improved management and local materials. Using simple techniques, even the poorest resourced farmers can have some direct control over postharvest pests. The use of biorational approaches to control stored product pests has been reviewed recently (Phillips and Throne 2010), so this chapter will focus more specifically on the potential for plants to be effective alternatives to pesticides. Plant species have been studied for decades as potential alternatives to commercial synthetic chemicals owing to their abundance of defence chemicals, and it has been estimated that around 10 % of all plant species (~28,000) have some pesticidal chemical qualities but fewer than 500 have robust evidence supporting the reported activity (Simmonds 2003). Plants have not fulfilled their commercial promise and are perhaps best suited to providing important, and for some of the poorest resourced farmers the only, source of pest control material in developing nations (Isman 2006, 2008). Plants offer an economically viable alternative for small-holder farmers, but the research to develop them is lacking robust chemical backstopping, and their effective promotion, using applications that are improved based on scientific research, could improve their impact and sustainability for storage pest management for insect pests.

In most cases, the idea of using plant material to control pests is a familiar concept to farmers (Kamanula et al. 2011; Nyirenda et al. 2011), and many recognise their wider benefits as environmentally benign, less toxic and cost-effective compared to synthetic pesticides. Plant materials are also more difficult to adulterate especially if they are harvested by the farmers themselves, and while they may not require any significant financial outlay, their use does consume one important resource to farmers – time.

Farmer surveys carried out in Ghana have highlighted that many farmers do not use commercial synthetics (Belmain and Stevenson 2001)

and, instead, use plant-based products. While there is a general acceptance that plants offer a useful alternative to commercial pesticides for small-holder farmers, some recent surveys reveal that elsewhere in Africa surprisingly few actually use them (Kamanula et al. 2011). This could be explained by knowledge gaps or failing policies to drive uptake or commercialisation. Availability of plant material and variability of that material are major limiting factors, and the propagation and commercialised cultivation of key verified or validated provenances could drive the change needed to enable more farmers to use this technology and establish plant materials as a genuine alternative to pesticides.

This chapter draws attention to knowledge gaps in aspects of pesticidal plant research and promotion and provides guidance on how scientists can better target their research to ensure that outcomes offer useful knowledge that can improve uptake and use of pesticidal plants. Much of this work has been carried out under the African Dryland Alliance for Pesticidal Plant Technologies (ADAPPT Project) and continues through propagation and outreach activities on a follow-up strategy Optimising Pesticidal Plants: Technology Innovation, Outreach and Networks Project (OPTIONs).

An analysis of published science based in Africa on pesticidal plants indicates that much research overlooks the critical knowledge gaps and is repeated work or delivers outputs that are unlikely to have any impact on agricultural development and poverty alleviation. Most research on pesticidal plants does not address the problems that limit the development, uptake and promotion of pesticidal plants. Furthermore, >80 % of published work in this research area in Africa reports laboratory bioassays that simply evaluate pesticidal plants against insects with little consideration of the information needed to optimise use, facilitate upscaling, enhance field efficacy or address health and safety issues (vertebrate toxicity), propagation, cultivation or conservation. This is particularly well illustrated by the example of biological activity reported in nonpolar extracts of a plant against a pest species that farmers will attempt to control in the field using

crude water extracts that will unlikely contain any of the active components reported in the scientific study.

Ideally to be effective and useful in stored product protection, plant materials need to show low toxicity to mammals and the environment, show toxicity or repellency to a wide range of target species, have efficacy at low doses and with a long period of activity, have low cost in terms of time to collect process and apply, be compatible with other pest management technologies, be stable chemically and have no consequences for the stored product such as impairing flavour.

2 Pesticidal Plants as Alternatives to Synthetic Products in Africa

Generations of African farmers have used pesticidal plants to control stored product pests (Thacker 2002), and prior to the synthetic chemistry revolution, plants were the only technology available to farmers for insect pest control (Isman 2008). There are already many literature reviews about pesticidal plants and here we do not attempt to repeat this. Prakash and Rao (1997) have reviewed botanical insecticides describing biological activities and applications for >100 species, while details of plant chemistries and their role in integrated approaches to pest control pest are also reviewed (Koul and Dhaliwal 2004).

The main objective of this chapter is to highlight the importance of pesticidal plants as alternative pest control technologies for stored products and draw attention to knowledge gaps for future research based on what is absent from recent published work. Despite thousands of research articles in the literature, there are only a handful of successful commercial botanical products used for insect control including pyrethrum, rotenoid-based products, neem and essential oils. Thus, plants as commercial products have fallen short of their potential (Isman 2006). Indeed they comprise only a small fraction of the total pesticide used in high volume agriculture in Europe, Australasia and the Americas. However, in Africa they still have a major contribution to make for

farmers, and it has been argued convincingly that it is for the rural poor that pesticidal plants have the greatest value in agriculture (Isman 2008). Many of the species available and used in Africa are described in detail by Stoll (2000) along with low-tech practical application procedures for a variety of pests and crops that require the minimum preparation. This is distinct from the aspiration of many scientists whose aim is a commercial product in a bottle that replaces a synthetic product. Here, we focus on pesticidal plants that comprise crude plant materials including leaves, stem bark, roots, fruits and seeds that are effective but need only rudimentary preparation and are thus more suitable for the resource-poor small-holder farmers across Africa. This processing includes drying, crushing and mixing with stored products (Belmain and Stevenson 2001) or producing crude extracts in water for application with a sprayer or applied using a brush (Stoll 2000). Indeed the lower the level of preparation that is required, the more universally appropriate the plant material. This is not to say that the materials do not require effective and robust backstopping with scientific knowledge and research. Indeed we argue below, using examples from our own work and recent work of others, that scientific support is essential to provide farmers with reliable products and materials that have predictable and measurable effects.

Kamanula et al. (2011) reported that farmers are well aware of the potential pesticidal value of plants but, depending upon the country, only between 20 and 50 % actually used them. This may be because efficacy is perceived to be lower than with the other available pesticides, or the inconsistency in efficacy could explain it. We expand below on how this has impacted on the use of pesticidal plants and how it might be overcome. However, for small-holder farmers who have no alternatives, some efficacy is better than none even if only a moderate reduction in damage can be achieved. Optimising efficacy through adaptations of the application based on understanding the chemical mechanisms and developing processes for their application that exploit this knowledge could improve uptake. There are key research areas that need attention

in the optimization of the use of plants in pest control and are discussed later below.

The last 10 years has seen an explosion in the productivity of entomologists and related scientists identifying new plant materials with new biological activities against old storage insects pests, e.g. Ali et al. (2013), Padin et al. (2013). While this is useful and adds to our ever increasing resources of plant materials, the majority of these research outcomes do not provide any chemical basis for the biological activities reported and as such lose much potential impact. In some cases this is a serious oversight but perhaps more often simply indicates the limitations of laboratories working in this research domain.

A chemical comprehension of biological activity in pesticidal plants is important because chemistry can show extreme variation in plant material from the same species (Stevenson et al. 2012). Consequently it can be a serious limiting factor in its effective and reliable use as a pesticide whether in commercialised products or simply for crude use by poor farmers (Belmain et al. 2012). We will discuss how important this can be in more detail in subsequent sections of this chapter, but it is sufficient to say that the natural variation within populations of plants manifests itself in chemical as well as morphological diversity. One way to control for this is to carry out bioassays using plant materials from several different locations within the target region in field trials compared to a commercial synthetic pesticide which can be carried out in different locations and indicate the level of variation in efficacy that farmers might expect in plant materials being tested (Amoabeng et al. 2013).

A recent review of plant feeding deterrents for stored product pests provides a summary of 200 compounds primarily sesquiterpenes identified to date and illustrates the depth of options available to researchers of plant pesticides for stored products pests (Nawrot and Harmatha 2013). However, most research published in the last 10 years does not determine the chemical basis of the biological activity, and those that do report the identification of chemicals are investigating plants for their essential oils (Zhao et al. 2013;

Liu et al. 2012). This is likely in many cases because target molecules in essential oils research can be identified using routine equipment (Gas Chromatography-Mass Spectrometry), and the now universal National Institute of Standards and Technology (NIST) mass spectrometry library can be used to assert a high probability of correct identification of many small molecules based on their fragmentation pattern from easily sampled material. Essential oils are also studied with a view to commercialisation since they are Generally Regarded as Safe, and so circumvent regulatory procedures in North America (Isman et al. 2011) may perhaps prove to be more commercially viable botanical insecticides than many plant pesticides that rely on more intrinsically toxic chemicals for their activities. One major issue working with essential oils is that where the biological activity of plant material is reported to be associated with the essential oil content, the pure compounds are tested at much higher concentrations than occur in the plant and so can be misleading about their potential effect in unprocessed plant material. Because the yields of essential oils are often very poor from plants, the costs of using essential oils at some of the concentrations proposed are high for large-scale agriculture (Jiang et al. 2012b).

Determining the structures of compounds from other main groups of natural products in plants that might account for the biological activity of plants is otherwise overlooked. This may be because the specialised spectroscopic instrumentation including LC-MS, Prep HPLC and NMR required to isolate and determine structures of large and often structurally complex molecules is not widely available nor the expertise to use the equipment, where available. This is particularly problematic if compounds are new or there are no literature data to compare. The consequence is that some of the most interesting new plant-based pesticidal discoveries do not advance the subject as far as they might have done as we do not know what the active components are. Another oversight that reduces the value of much recent research is that the plant material is not always botanically verified by a qualified botanist, and researchers do not deposit specimens in

registered herbaria so that the work can be later revisited, verified and further studied by future researchers who might have access to the material tested in the published reports. The importance of herbaria is well presented by Funk (2004). Herbarium specimens necessarily require associated information including locality including the country, habitat, altitude, field identification and location (including GPS coordinates), date of collection and plant description all of which are essential information for anyone who might wish to use a specimen at later date or inform about the research published about the specimen in the first place (Bridson and Fornan 2000). A specimen collected at one time of the year or a specific location might be chemically and biologically different to one collected at another time or location. The New York Botanical Garden Index Herbariorum provides a list of accredited herbaria around the world, and this can be helpful. The value of herbarium material cannot be overstated and can even provide chemically important and reliable material for many decades. For example, a study analysing fresh leaf material of *Tetradium daniellii* compared extracts with a herbarium specimen collected in Yunnan province, China, in 1917 to verify the material and the chemistry of furanocoumarins was almost unchanged after 90 years (Stevenson et al. 2003).

Correct identification is critical but not always robust. The authors of this chapter have encountered many examples of incorrectly identified plant material being used in internationally funded research. For example, work published by Kestenholz et al. (2007) provided important work understanding how *Cassia sophera* (Leguminosae) could be used in storage protection against *Sitophilus oryzae,* but the plant material when originally sourced was described at *Cissus populnea* (Vitaceae), a quite different plant. Similarly, Stevenson et al. (2012) report perhaps the most widely used pesticidal plant material in Africa, *Tephrosia vogelii*, being incorrectly identified and promoted for use by farmers as *Tephrosia candida* and reported as such in numerous scientific papers over the past 20 years that is potentially highly confusing (Jama et al. 2008; Sileshi et al. 2005).

Increasingly, the application of organic solvent extracts is considered to adequately provide a step towards a better understanding of biological activities (Ortiz et al. 2012) but in reality does not necessarily inform any more than simply using powdered plant material and may even confuse our knowledge. More frustratingly some recent research indicates 'phytochemical screening' in the title but then actually simply assays extracts (Adeniyi et al. 2010; Udo 2012).

There are few reports of plant materials that do not work, but this is also important since the impression from the literature is that otherwise it seems all plants tested have activity (Baoua et al. 2012), while the majority are focused on laboratory bioassays and not on field trials.

3   Research Priorities for Improving Uptake and Use of Pesticidal Plants for Stored Product Pests

3.1   Understanding the Chemistry of Activity

As mentioned earlier, the use of pesticidal plants requires a strong understanding of the chemistry underlying the biological activities. At the very least this will help to understand variability in efficacy as determined by the testing of plants from different locations, but for most published research, this has been overlooked. This is required to enable intelligent enhancement of activities by improved application, a stronger understanding of the potential toxicities associated with plant material, improved harvesting strategies and potentially identifying new sources of chemicals where plants currently used are threatened through overharvesting or ecological limitations. Abundant plants with similar chemistry to a scarce but over harvested species could be promoted as an environmentally benign alternative.

The importance of understanding the chemistry is well illustrated by some recent research on *Tephrosia vogelii. Tephrosia* Pers. (Leguminosae) is a large genus of more than 350 species, many

of which have important uses (Schrire 2005). *Tephrosia vogelii* Hook. f. is one of the best known of these species and is widely used in Africa (Kamanula et al. 2011; Nyirenda et al. 2011). The species is promoted for its ability to enrich soil both through biological nitrogen fixation but also as a green manure (Mafongoya and Kuntashula 2005; Sileshi et al. 2005; Sirrine et al. 2010) as well as for its pesticidal use and fish poisoning properties (Burkill 1995; Neuwinger 2004), although the latter application is now prohibited. As a consequence, it is cultivated widely by farmers on fallow land.

Much literature, particularly in unrefereed articles and on-line pamphlets, ascribe the biological activity of the species against storage pests to rotenoids and specifically to rotenone. Much of this is, however, assumed and unsubstantiated based on historic research identifying components in the plant that show the major rotenoids in the leaves are deguelin and rotenone (Irvine and Freyre 1959). While much 'grey' literature cites rotenoids in the leaves of *Tephrosia* to be insecticidal against stored product pests, surprisingly there is no published work to corroborate this. Indeed the bioactivity of *T. vogelii* against bruchids and weevils was even reportedly *not* associated with rotenoids according to Koona and Dorn (2005) although this was based solely on their finding that the biological activity of *T. vogelii* was associated with hexane extracts, and the authors assumed that hexane would not extract rotenoids.

Belmain et al. (2012) have, however, now shown categorically that rotenoids are indeed the biologically active compounds in the species to bruchids but report that rotenone itself plays only a relatively minor part in this effect compared to the much more abundant compound deguelin (Fig. 9.2). Interestingly, the structurally related rotenoid tephrosin was much less active than deguelin despite differing only in one additional hydroxylation indicating that not all rotenoids have similar activities, so assumptions about potential pesticidal efficacy must be avoided without evidence. Two other rotenoids identified in *T. vogelii* (sarcolobine and toxicarol) (Fig. 9.2) had similar biological activities to deguelin (Stevenson et al. 2012). The highest

concentration of the active compounds is found in the leaf which makes it ideal for use since the foliage is the most abundant and sustainably harvested plant part. Besides this, it is relatively easily cultivated so is a species least likely to have any environmental impact if wild harvesting is not required. It is clear that the potential livelihood impact of this multiple use plant is compelling, and while it is well suited to resource-poor farming and is cultivated widely in southern and eastern Africa for soil improving qualities and as a pesticide, not all farmers reported that *Tephrosia* was a reliable pest control agent (Nyirenda et al. 2011). This could be because chemical content of leaves varied and so influences the pesticidal efficacy of *T. vogelii* since the activity of rotenoids is concentration dependent (Fang and Casida 1999). The occurrence of these compounds did vary dramatically among plant material sampled from 13 different locations in Malawi while deguelin and rotenone were in fact absent from approximately 25 % of sampled material (Stevenson et al. 2012). Indeed two distinct chemotypes have been proposed – one contains rotenoids which was the pesticidal one, while the second did not contain rotenoids but instead contained flavanones and flavones such as obovatin 5-*O*-methyl ether (Fig. 9.2), which was not pesticidal. This distinct chemical variation within a species likely explains the experience of some farmers who reported no pesticidal effect and highlights how important it is to understand chemistry since this enables us to understand why efficacy varies or is lost. Also – as has been the experience of farmers in Malawi – promotion of material for which an ascribed use is associated or simply presumed can seriously backfire if the material is not verified first.

This is as true for bioassays as assumptions made about chemistry. Earlier work asserting that the biological activity of *Tephrosia vogelii* was not associated with rotenoids based on an assumption that hexane extracts, which were active, could not contain rotenoids is misleading (Koona and Dorn 2005). Indeed, unpublished work in our laboratory indicates that hexane does extract rotenoids from *T. vogelii* leaves, and so rotenoids in this work almost certainly did account for the biological activities reported.

T. vogelii - chemotype 1 compounds
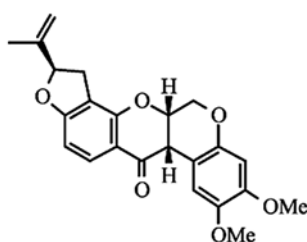
1 Rotenone
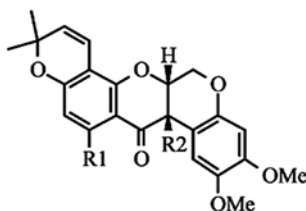
2 R₁ = H, R₂ = OH; Tephrosin
3 R₁ = R₂ = H; Deguelin
4 R₁ = OH, R₂ = H; α-Toxicarol
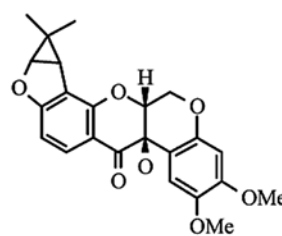
5 Sarcolobine

T. vogelii - chemotype 2 compounds
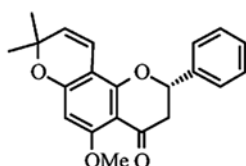

6 Obovatin-5-*O*-methylether

Fig. 9.2 The principal rotenoids and flavanones identified in chemotypes of *Tephrosia vogelii*

The solubility of the compounds from *Tephrosia vogelii* raises another important point. One of the benefits of understanding chemistry of activity is that current uses can be better understood and adapted with this new information. For example, some farmers report using *Tephrosia* extracts as a pesticidal spray but only have access to water as an extraction solvent. Rotenoids are only sparingly soluble in water and so this process is highly inefficient. Of course organic solvents are out of the question as they are unavailable and expensive and could potentially damage plants. Comparative analysis of the extraction efficiency of water carried out by Belmain et al. (2012) compared the extraction efficiencies of methanol with water and showed that it extracted 10.0 times as much deguelin as water. However, the extraction with Tween 20 increased the efficiency of water for rotenoids by almost three times using 1 % Tween 20 and by near 5 times using 5 % Tween 20. Thus, if farmers use *T. vogelii* extracts to treat grain or grain sacks, efficacy could be improved, and the amount of plant material required could be reduced by simply incorporating a detergent such

as liquid soap which might additionally act as a surfactant and spreader and further optimise application and improve efficiency.

The compounds identified as biologically active in some plants have been reported to be water soluble such as triterpeneglycosides (saponins). These might be more sustainably exploited and more efficiently applied as water extracts than the typical application process in stored products – powdered plant material. In their search for new bioactive plant compounds against *Sitophilus oryzae*, Taylor et al. (2004) reported saponins from field pea extracts that were at least partly responsible for the anti-feedant effects of pea flour extracts. Elsewhere, saponins present in *Securidaca longepedunculata* (Polygalaceae) (Stevenson et al. 2009) have also been identified as contributing to the long-term biological activity of the roots of this species. *S. longepedunculata* (African violet tree) is a small tree occurring throughout sub-Saharan Africa. Farmers reported using the roots of this species for stored products in Ghana, and evidence indicates that *S. longepedunculata* was effective against *Rhyzopertha dominica*, *Callosobruchus*

Fig. 9.3 Securidacasides from roots of *Securidaca longepedunculata*
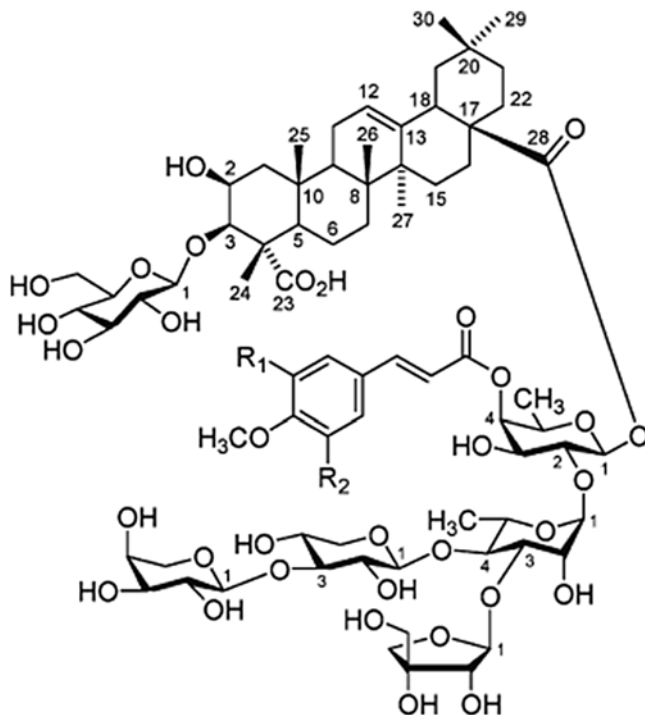
1 R$_1$ = R$_2$ = H; Securidacaside A
2 R$_1$ = R$_2$ = OCH$_3$; Securidacaside B

maculatus, *Sitophilus zeamais* and *Prostephanus truncatus* when compared to *Cassia sophera*, *Chamaecrista nigricans*, *Mitragyna inermis*, *Ocimum americanum* and *Synedrella nodiflora* which are other species reported in the Northern Region of Ghana to be used traditionally for pest control in stores (Belmain and Stevenson, 2001), and this is now supported by laboratory data (Jayasekera et al. 2003). When evaluating 33 West African species for toxicity to *C. maculatus*, Boeke et al. (2004a, b) also showed *S. longepedunculata* along with *Nicotiana tabacum* and *T. vogelii* to reduce F1 progeny of the beetles, while *Clausena anisata*, *Dracaena arborea*, *T. vogelii*, *Momordica charantia* and *Blumea aurita* were shown to be repellent. Surprisingly this study reported *Azadirachta indica* was attractive along with *Chamaecrista nigricans* and *Hyptis*. The roots of *S. longepedunculata* also have a characteristic odour of wintergreen, and the principal volatile compound in the root was shown to be methyl salicylate (Jayasekera et al.

2002), and this compound was shown to have toxic effects against several beetle species (Jayasekera et al. 2005) and could enhance the effects of the saponins reported above. Water-soluble compounds could be used to reduce the amount of plant material required by extracting the chemicals and so using plants more efficiently. We conducted a trial on a farm in Zambia to determine whether applying *S. longepedunculata* root bark was more efficient. Farmers reported they needed around half as much plant material but also insisted that they would never use the method as it was too time consuming compared to simply grinding up the roots and adding to their grain stores (Zulu and Stevenson, unpublished). This highlights another important condition of optimising the use of plant materials. Any improvement must be trialled and accepted by farmers to have any chance of being adopted (Fig. 9.3).

The chemistry of some plants varies according to the season, the plant age and location, so

chemical analysis is essential to determine the best time to harvest or for identifying elite material for propagation (Sarasan et al. 2011). Of course the need to use fresh plant material over dry might determine harvesting priorities but chemical knowledge of the active components would certainly optimise harvesting times. The ability of many African laboratories to carry out this analytical work is limited to a handful of institutes. Cooperation through research networks is essential to move this area of work forward, and expertise and equipment in natural product chemistry need to be expanded.

Chemical analysis using tandem-linked detection techniques such as mass spectrometry can maximise information acquisition of compounds in each plant and can identify many components quickly, particularly seasonal variations and genotypic differences between specimens of a single species to better understand the potential variation in efficacy. These techniques can also be used to authenticate specimens before promoting widely. While these facilities are beyond the reach of many research institutes, many materials could be authenticated by less costly techniques such as thin layer chromatography.

3.2 Understanding the Target Pest

As with ensuring correct identification of plant material, it is important to ensure that the insects on which a biopesticide or potentially efficacious plant preparation is being tested really are the species they are supposed to be. Although in many cases, similar insects (e.g. *Sitophilus zeamais* and *S. oryzae*) will mostly respond similarly to biopesticides, subtle differences in ecological niches between species can result in differential behavioural or physiological responses to control measures. For example, Champ and Cribb (1965) found that *S. oryzae* was more susceptible to the insecticide diazinon and ronnel than *S. zeamais*, and *S. zeamais* is also more resistant to low temperatures than *S. oryzae* (Nakakita and Ikenaga 1997). It follows that testing of plant-derived pesticidal products may show similar susceptibility differences between closely related species.

Understanding the biology of the pest is key to understanding how to control it. In the case of storage pests, the insect species predate human agriculture and grain or legume storage in man-made structures, so the insect's ecology before that will provide keys to management strategies. For example, some cereal pests such as *Prostephanus truncatus* and *Rhyzopertha dominica* were originally wood-boring beetles which adapted to exploit grain stores, so their responses to odours have more in common with other wood-borers (e.g. no innate response to cereal odours (Fadamiro et al. 1998; Nguyen et al. 2008)).

It is easy to look at a sack of infested grain, legumes or other stored product and see only a mass of insects to be tackled in bulk, and indeed this is the approach taken in many studies. However, when devising control strategies it is more helpful to visualise the population as a collection of *individuals*, some male, some female, all at different life stages, and thus not all responding identically. They interact with one another but also behave independently – and diversely – in response to some cues. This is especially true in terms of behavioural syndromes associated with responses to odours, and odour-based repellency can be a key component of effectiveness for some pesticidal plants. It is well known that males and females of many insect species exhibit differential responses to sex pheromones; this has been observed in many groups of insects, including moths (Matsumoto and Hildebrand 1981) (though see Palanaswamy and Seabrook (1978)), beetles (Ukeh et al. 2008), Hemiptera (Ondarza et al. 1986; Manrique and Lazzari 1995) and braconid wasps (Kimani and Overholt 1995). However, equally, males and females do not always respond the same way to aggregation pheromones (Byers 1983; Walgenbach et al. 1983; Ondarza et al. 1986) or odours associated with host material (e.g. fresh plant matter, cereals, mammal odours). Sex differences in responses to host material have been recorded across the Insecta, in moths (Hansson et al. 1989), parasitoid wasps (Bouchard and Cloutier 1985), Hemiptera (Chinta et al. 1994; Wenninger et al. 2009), beetles (Zhu et al. 1999; Ukeh et al. 2008), tsetse (Otter et al. 1991), etc.

Sometimes this is related to differences in lifestyle habits between the sexes, for example, if the females seek host material for oviposition rather than personal consumption or in species where the female requires a blood meal, but it can also occur in species where both sexes feed on the same material. Consequently, bioassays testing unsexed individuals run the risk of assuming that males and females are controlled equally well without actually proving this to be the case.

Recent research has found differences in male and female responses of the cowpea weevil, *Callosobruchus maculatus*, to both host odours and the plant-derived repellent, methyl salicylate (Arnold et al. 2012). Females showed a significantly stronger preference than males for infested cowpea material (Fig. 9.4). These findings make evolutionary sense as females must seek safe host material for their offspring to consume during development and therefore are under pressure to use olfactory cues to aid this process. Males, conversely, seek virgin females and so have no particular reason to seek out uninfested cowpea as adults; however, they may target heavily infested material as virgin females may emerge from it.

Differential responses to the plant-derived repellent methyl salicylate are also apparent in the findings, with older, inactive-morph females repelled by methyl salicylate but weaker responses from some other subgroups of *C. maculatus*. As methyl salicylate is an active component of pesticidal plants such as *Securidaca longepedunculata,* etc., the finding that it is not equally reliable as a repellent of male and female *C. maculatus* is a notable one and should be taken into account when devising application strategies.

However, it is not just the sex of an insect that can determine its odour-mediated responses. Several insect species are dimorphic, with morphs better adapted for static breeding or for dispersal – this is particularly common in aphids (alate and apterous morphs) and also bruchid beetles (in which the morphs are termed 'active' and 'inactive' or 'flight' and 'flightless', etc.). Jaba et al. (2010) found responses of *Aphis craccivora* alates were higher to odours of fresh cowpea but lower to odours of *Lablab dolichos* compared with the responses of apterous indi-

viduals (Jaba et al. 2010). Equally, different sensory physiology has been observed in solitary and gregarious locusts, with a physical change in the numbers of sensilla on antennae when they switch morphs (Greenwood and Chapman 1984).

C. maculatus has both an 'inactive' morph, which is virtually flightless and short-lived, but the females have high fecundity, and an 'active' morph, which can fly and has a longer lifespan, but has limited fecundity (Caswell 1960; Utida 1972). Production typically switches to the active morph in response to extremes of temperature, photoperiod or humidity, degradation of the larval host material or overcrowding (Messina and Renwick 1985; Utida 1972). While both forms can potentially be the source of an infestation, it is typically expected that the active form will infest beans still in the field by flying in, whereas the inactive form is more likely to be introduced on infested material or emerge later from beans infested in the field. In spite of this, many laboratory tests on this species do not differentiate the morphs (and some long-term lab cultures are believed to produce only active morph adults). The differences in their typical lifestyles suggest that it might be expected that the morphs would respond differentially to host odours. Arnold et al. (2012), confirmed this, discovering that morph interacted with age as a factor to affect preferences for host odours and that inactive individuals were more attracted to dried cowpea than were the active morph individuals (Fig. 9.5). What is less easily anticipated but also extremely relevant for control based in part on repellency is that we found a similar differential response between morphs to the repellent odour, methyl salicylate. In their four-arm olfactometer experiment, the inactive morph was strongly repelled by the odour, whereas the active morph was indifferent (Fig. 9.6). This means that control strategies based upon the repellent properties of methyl salicylate or plant material containing it are best deployed to target the inactive morph, for example, within the stores and at ground level, and other methods may be required to ensure control of the active morph in fields and above-ground.

Further work also showed that sensitivity to odours can change depending on the age of the

Fig. 9.4 Preferences of female and male *Callosobruchus maculatus* for insect-infested and uninfested cowpea material, tested in a four-arm olfactometer. 25 % indicates no preference (Data from Arnold et al. (2012))
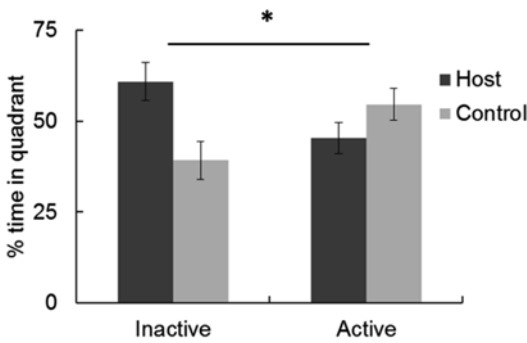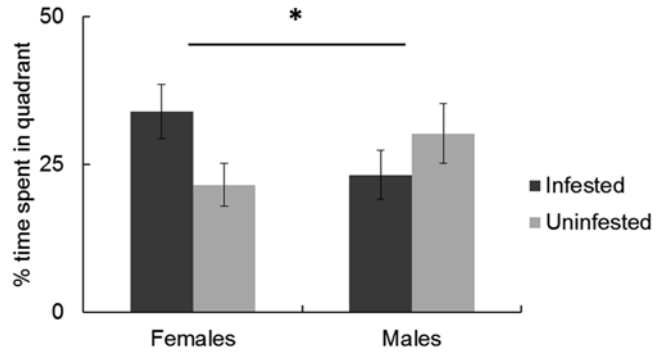

Fig. 9.5 Time spent in the presence of host (cowpea) and control (clean air) odours by inactive and active morph individuals of *C. maculatus* in a four-arm olfactometer with two arms containing host odours and two arms control odours. 50 % indicates no preference
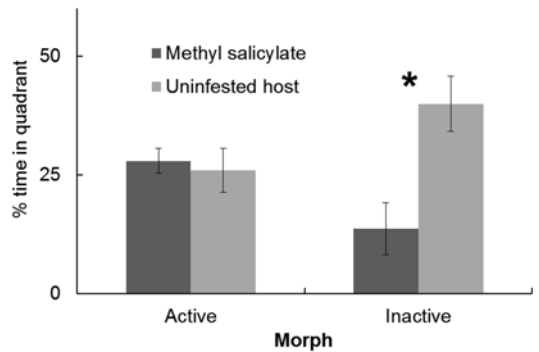

Fig. 9.6 Responses of active and inactive morphs of *C. maculatus* to the odour of 1 mg/ml methyl salicylate versus host odours in an olfactometer experiment. 25 % indicates no preference

insect, and therefore older as well as newly emerged individuals should always be tested when evaluating the effectiveness of a repellent or bait in order to ensure that acclimation to an odour does not occur. Furthermore, it is worthwhile comparing a variety of strains of the pest insect to evaluate whether behavioural and physiological susceptibility to a biopesticide is consistent for all subpopulations within the species or whether it is variable. Given the capacity of various stored product pests to evolve insecticide resistance (Champ and Cribb 1965; Champ and Dyte 1976; Collins et al. 1993), the possibility of some strains eventually evolving either physiological resistance or behavioural tolerance to biopesticides or plant-based repellents is not unthinkable. Characterising interstrain sensitivity to biopesticides will permit geographical optimisation of application of the plant material – as a hypothetical example, there would be little point

promoting neem for control of *P. truncatus* in India if only the African strain of the insect were proven susceptible. This can equally apply to plant-derived repellents and deterrents: different strains of mosquitoes have been found to show diverse levels of repellency when exposed to diethyl toluamide (DEET) (Rutledge et al. 1978), so we may see strains of insect for which some ordinarily effective plant volatiles or essential oils are simply not deterrent, and it may be short-sighted to assume geographical homogeneity in odour responses.

Finally, behavioural responses can also be determined by aspects of physiological status. Malaria-infected mosquitoes have been shown to be more responsive to host odours (Smallegange et al. 2013), and likewise, feeding and parity status have been shown to affect both their attraction to host odours (Klowden et al. 1996) and their repellency responses to pyrethroid insecticides

(Chareonviriyaphap et al. 2006). Mated and unmated individuals of several insect species (Mechaber et al. 2002; Wenninger et al. 2009) likewise have been shown to exhibit differential responses to odours. This includes the stored product pest *Tribolium castaneum* – in one study (Fedina and Lewis 2007), unmated individuals consistently responded more strongly to a lure based on synthetic aggregation pheromone than did mated individuals. Feeding status also influenced their olfactory responses. Various bruchids (Leroy et al. 1999) are found to have changes in olfactory sensitivity according to mating status, and furthermore, there were found to be annual cycles in the beetles' responses to host odours. It is therefore advisable to take into account possible effects of mating status, for example, by testing both mated and virgin individuals, and of feeding status by rearing all insects on consistent medium and controlling for the period of starvation before testing.

Mass-testing protocols have their value: they allow a large number of insects to be tested in a short space of time and, under some circumstances, including the conspecific interactions may be a more accurate reflection of insect behaviour in the field. However, it is not always so simple. If, within a species, thresholds for responding to an attractive odour vary, are those 100 insects all sitting in the area of odour because they are all attracted to the test odour, or did only one of them truly respond to the test odour and the rest simply flocked to be close to their conspecific, as a result of aggregation pheromone or otherwise? This would have implications for trapping, as a lure to which only 1 % of insects respond, would be of limited use. One could argue that if the other insects follow the first into the trap, it does not matter what they are following, but what if the first insect dies and then lacks the attractiveness, so the remaining 99 % do not respond at all? Consistent individual responses may be a more reliable clue to the effectiveness of a strategy in many cases. Although time consuming, when testing individual insects the quality of the data will be higher, and it is possible to control for multiple factors (age, sex, strain, morph, mating status).

Care must be taken when performing laboratory evaluations of the pests' responses to odours using some items of equipment. It is easy to predict that when an insect is presented with an airstream containing an attractive odour, the insect will walk or fly upstream towards the odour source. However, how will the same insect react if the odour is aversive, such as repellent pesticidal plant material? Will it simply stop walking? Will it move perpendicular to the direction of airflow? Will it turn around and fly downstream? The unpredictability of these responses makes it hard to use some pieces of equipment to investigate repellent odours. An example is the locomotion compensator. While *S. zeamais* shows clear aversion to methyl salicylate in the four-arm olfactometer (Jayasekera et al. 2005) and clear attraction to maize odours in both the olfactometer (Fig. 9.7) (Ukeh et al. 2010, 2012) and on a locomotion compensator (Fig. 9.8a), it does not respond at all to methyl salicylate on the same piece of equipment (Fig. 9.8b). Similarly, in a Y-tube olfactometer, while if one arm is attractive and the other a blank control, it can be assumed that most insects will fairly reliably walk up towards the fork in the tube and then make a decision, ordinarily turning towards the attractive odour; what if one of the arms has a repellent odour? In that case, the repellent odour is drawn through the 'error' arm, but then onwards through the approach arm, so even at the start of the experiment when the insect is in the approach arm, unless it is established that airflow is perfectly laminar, it is receiving a stream of air tainted with a repellent odour. Why, then, should we expect it to meekly walk into this repellent odour stream all the way to the decision point at which the olfactometer branches before deciding to turn away from the scent?

3.3 Safety of Use of Pesticidal Plants

Natural does not necessarily equal safe, despite frequent implication of this in the modern comprehension of 'healthy'. Some plants are, in fact,
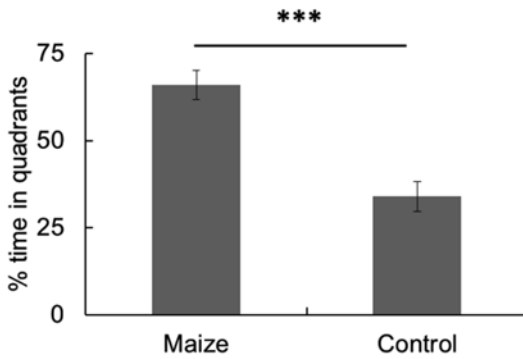
Fig. 9.7 Responses of *Sitophilus zeamais* to maize odours in a 4-arm olfactometer (2 arms with odour, 2 arms with clean air only; 50 % indicates no preference)

extremely toxic, such as *Taxus* spp., *Aconitum* spp. and, perhaps most notorious of all, *Ricinus communis* (Bonnici et al. 2010; Hernandez et al. 2010; Kuca and Pohanka 2010; Kolev et al. 1996). Plant materials used as pesticides are toxic, at least to insects, so safe use is particularly important in this respect as they are used to treat stored foods when used to control storage pest insects. Yet inadequate work has been published internationally on the vertebrate toxicity of African pesticidal plants. This may be because the costs of commercialising pesticidal plants are prohibitive, so there are no requirements to test them officially. Some commonly found plants used by farmers in Ghana have been shown to affect mammalian growth and development (Belmain et al. 2001).

Some plants consumed as an ingredient in food and drinks indicate a degree of safety and are the basis for the promotion of essential oil products in North America (Isman 2006). However, even where plants are used as food or drink, they may still show some toxicity. *Lippia javanica,* for example, is a popular treatment for fever in Southern Africa where it is drunk as a green tea. This species also showed acute oral toxicity in mice at very high concentrations (Madzimure et al. 2011). Nyahangare et al. (2012) also evaluated toxicity associated with *Strychnos spinosa* and *Bobgunnia madagascariensis* fruits and the foliage of *Vernonia amygdalina* and *Cissus quadrangularis* and found the
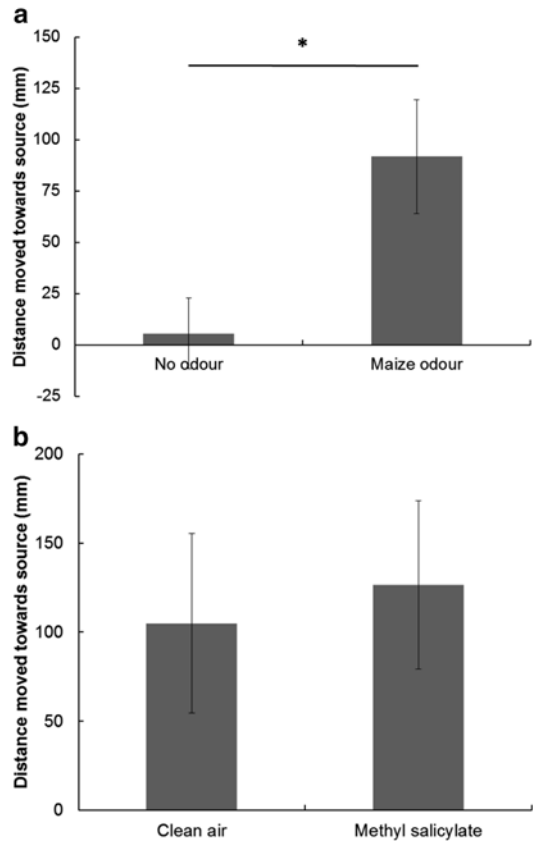

Fig. 9.8 Responses by two groups of *S. zeamais* to (**a**) maize odours and (**b**) methyl salicylate on a locomotion compensator, showing the distance walked by individuals towards the odour source either in the absence or presence of the odour

first two to be toxic when administered at high doses but the latter two much less so.

Plants are typically applied as pesticides using amounts that present toxic components at low levels and so rarely pose any significant acute toxicity to users (Isman 2008) even when this is intended (Chesneau et al. 2009). Belmain et al. (2012) report that to suffer a lethal dose from consuming *Tephrosia vogelii,* a fully grown man would need to consume between 2 and 20 kg of dried leaf at one sitting.

Postharvest insect pest control in small-holder farming in Africa relies primarily on pirimiphos-methyl, an organophosphate that targets anti-cholinesterase. Where pest complexes include *Prostephanus truncatus*, the larger grain borer,

pirimiphos-methyl is combined with permethrin (Sekyembe et al. 1993). Safety sheets for Actellic EC50 (pirimiphos-methyl) indicate moderate toxicity to mammals and extreme toxicity to aquatic invertebrates and are highly toxic to algae and fish (Syngenta 2006). Thus, fears over the toxicity of plant species like *Tephrosia vogelii* that are very popular alternatives to pesticides in southeastern Africa (Kamanula et al. 2011; Nyirenda et al. 2011), but have known toxicity to fish, are perhaps over cautious. A no cost but effective plant-based alternative should be considered a viable option for very poor farmers, but without commercialisation – which is unlikely in the current climate (Sola et al. 2013) – the wide-scale uptake seems unlikely. The best approach could be through the development of better propagation protocols and widespread cultivation.

A possible solution may be to develop ways to apply pesticidal plants that minimise their contact with the actual foodstuff, either by layering the plant and the food alternately or by applying the plant to the container or cover, rather than mixing it into the food itself. Novel strategies for application or methods of synergising more and less toxic plants to ensure continued efficacy with low risk are promising directions for future research.

3.4 Sustainable Harvesting and Local Production of Pesticidal Plants

Demand for some plants – particularly medicinal species – is outstripping supply, driven largely by the fact that, even today, over 80 % of the world's population are dependent upon medicinal plants for at least part of their healthcare (Harnischfeger 2000; Shackleton et al. 2005). Overgrazing, conversion to farmland and bush fires also reduce potentially productive land for harvesting useful plants from the wild. The use of pesticidal plants, which typically requires very much larger quantities of material than medicinal uses, when collected from the wild is only sustainable if small numbers of people use the plant or if the plant is abundant and ubiquitous or propagated easily. Access to sufficient material is perhaps the

greatest constraint to wider uptake of pesticidal plant technologies among farmers; thus, ways to propagate and cultivate plant material will address this gap. If knowledge about efficacy can be determined and provenance selected based on chemical analysis, then propagated material can also be provided with a greater expectation of consistency in efficacy – so overcoming one the other major hurdles to wider uptake (Sarasan et al. 2011). Surprisingly little research is invested in aspects of propagation for pesticidal plants, with the exception of Pyrethrum, and this is largely for processing the active ingredient. However, medicinal plants and ornamental species are well studied to improve propagation (Gupta et al. 2012; Pijut et al. 2012), provide a greater pool of knowledge and be sourced for useful information where a species may provide pesticidal as well as ornamental or medicinal properties.

Propagation of medicinal plants is not always straightforward since conditions for successful germination vary considerably among species, and seeds may need some ecological hardship to induce germination such as long periods of dry weather or fire, in which cases artificial mechanisms may need to be used to overcome this – such as cutting the seed testa. Recent work has shown that some species can be propagated from seeds which could be important to establish large-scale cultivation of importantly pesticidal plants, particularly the tree species *Securidaca longepedunculata* and *Bobgunnia madagascariensis* (Thokozani et al. 2011; Zulu et al. 2011). Informed timing of seed collections is required and knowledge about seed drying, storage and germination are also important considerations.

In many cases, the part of the plant collected makes the technology highly unsuited to sustainable ecosystem management – for example, roots, bark, seeds or entire plants (Belmain and Stevenson 2001; Stoll 2000). Harvesting root bark, which may be as a consequence of following a scientifically unvalidated tradition, will likely kill the plant. Some research may identify active compounds in other plant parts such as the stem bark, which could be harvested more sustainably. Modified root harvesting such as only

taking lateral roots could reduce the impacts on abundance. Harvesting times can be important too. The chemistry of plants varies according to location and season (Stevenson et al. 2012; Belmain et al. 2012), and, since their efficacy as pest control agents depends on these variable chemistries, harvesting times can be crucial in optimising their efficacy.

Some plants produce the secondary metabolites that account for their pesticidal activity only when subjected to biotic or abiotic stressors, and this has not been investigated for many indigenous pesticidal plants. As an example from wider research, *Nicotiana attenuata* produces trypsin protease inhibitors to protect against insect attack, but only at high levels in its vegetative tissues when attacked by herbivores (Dinh et al. 2013; Skibbe et al. 2008). Knocking out the genes involved in inducing this defence leads to extreme vulnerability to pest attack. Such inducible defences allow the plant to save energy, as production of secondary metabolites is costly, so breeding a pesticidal plant for constitutive expression of the compounds in such cases may result in less vigorous plants. In other cases, the induction of production of active ingredient may be initiated by an abiotic stressor such as drought or photoperiod change (Ramakrishna and Ravishankar 2011).

If propagation can be established for species, then marketing plants as an income-generating opportunity for small-scale farmers may be a realistic ambition (Sarasan et al. 2011) while developing a way to upscale and promote a technology (Moyo et al. 2011). Technology outreach is limited by funding typically of short projects. If sustainable promotion can be driven by the incentive of income generation and a formalisation of pesticidal plant use for agricultural pest management in Africa, then the chance of wider uptake is increased (Grzywacz et al. 2014), particularly if government and non-governmental organisations continue to promote the use of wild plants. Demand for pesticidal plants will continue to grow, which can only realistically be met through their cultivation and marketing (Sola et al. 2013). The limitations of regulatory procedures could be the undoing of any potential pesti-

cidal plants as commercial products other than for those already established such as Pyrethrum. The regulatory processes are prohibitively expensive for small- and even medium-scale facilities and require any pesticidal product to satisfy the same level of interrogation regarding efficacy, toxicity and environmental hazard as synthetic products. This is, of course, right but the costs of producing most of the information are prohibitive and will continue to hold back wide-scale uptake. Conversely, the sale of herbal remedies in South Africa which are in many cases materials prescribed for oral consumption is unregulated, whereas a plant sold as a pest control product needs to be registered.

4   Pesticidal Plants for Stored Products in Southern Africa: Recent Developments for Selected Pesticidal Plants

Our recent work has combined surveys (Kamanula et al. 2011; Nyirenda et al. 2011) and databases (e.g. http://epic.kew.org) and has identified pesticidal plants of value as indicated by farmers themselves with interest particularly in Caesalpinioid (Miombo) woodlands. This list is not intended to be comprehensive but updates the research on some of the many species of interest in stored products protection while illustrating issues of importance to all pesticidal plant species. Some of the species reported by farmers are not supported by literature and so present new research opportunities. Having said that, there is an increasing argument towards better use of what we already have rather than investing time in evaluating more and more new material.

Euphorbia tirucalli, for example, is reported by farmers to be effective against stored product pests yet has only reported activity against two mosquitoes (Rahuman et al. 2008; Yadav et al. 2002). The latex of this species has potent skin irritant properties (Kinghorn 1978) which may be associated with the plant's activity and in practice may also dissuade use. Elsewhere, *Aloe ferox,* is reportedly burned and the leaf ash used to treat stored grain in Zimbabwe and Zambia (Phosiso

Sola, Pers Comm.), but there is no evidence to support the efficacy of this use. Another species reportedly used for stored product pest control is *Solanum incanum* but only recently has any evidence to support activity against arthropods published. Nyahangare et al. (2013) reports that the plant has biological activity against cattle ticks in field trials which show a potentially promising opportunity, but the species is also identified as potentially toxic to mammals (Nyahangare et al. 2012).

Many species reportedly used among farmers include non-native species such as *Cymbopogon nardus* and *C. citratus* and neem (*Azadirachta indica*). These species are some of the most well-studied species in the literature for their anti-insect activities and still provide research outcomes today (Chebet et al. 2013; Jiang et al. 2012a). *A. indica,* however, provides an important lesson in promotion of plant materials for pesticidal use. Most farmers we have encountered who report using neem use leaves presumably because the leaves are easily available and around all the time. But they are very low in their bioactive components (Koul and Dhaliwal 2004). Furthermore, in some highland regions of Southern Africa, the climate is too cold to allow flowering in this species *Azadirachta indica*; thus, the trees do not produce seeds (kernels) where the greatest quantities and diversity of pesticidal and deterrent compounds can be found. *Lantana camara* is another exotic species which is popular in some parts of Africa, e.g. Kenya and Algeria (Chebet et al. 2013; Zoubiri and Baaliouamer 2012). However, this plant does not appear to be used in Miombo regions of Southern Africa where it is considered highly invasive and receives high priority for local eradication programmes. Perhaps its use more widely could help control its spread by giving farmers a reason to harvest the plants.

Powders and essential oils of *Cinnamomum camphora*, *Ocimum basilicum* and *Chenopodium ambrosioides* and seeds of *Pimpinella anisum* were shown to be insecticidal against *Tribolium granarium* and *T. castaneum* (Nenaah and Ibrahim 2011), while Chu et al. (2011) have reported fumigant activity of *Chenopodium*

ambrosioides L. against *Sitophilus zeamais* and further report five compounds ((Z)-ascaridole, 2-carene,rho-cymene, isoascaridole and alpha-terpinene) of which (Z)-ascaridole recorded a LD50 against *S. zeamais* adults of 0.84 mg L^{-1} air with contact toxicity of 0.86 μg g^{-1} body. This species is easily propagated and as the active compounds are volatile (ascaridole) despite their being toxic should be easily evaporated from commodities and therefore pose little risk to consumers. However, applicators may need to take care.

Neorautanenia mitis (Leguminosae) is related chemically to *Derris*, *Lonchocarpus* and *Tephrosia* spp. The large underground tuber, which can weigh tens of kilos, has high concentrations of rotenoids, isoflavones and pterocarpans (Sakurai et al. 2006) and is relatively easy to propagate, thus like *Tephrosia* is conducive to cultivation by farmers. The principal active component is rotenone (Stevenson PC unpublished) although earlier studies have identified a variety of pterocarpans with potential antifungal activity (Sakurai et al. 2006) and earlier still reporting neotenone as the principal isoflavonoid component (Vanpuyvelde et al. 1987). Rotenone is well studied and there is much safety data on this compound, so in theory *N. mitis* is a good candidate for commercialisation. *N. mitis* roots are effective against a wide range of insects including the important mosquito species *Anopheles gambiae* and *C. quinquefasciatus* mosquitoes, with activities comparable to deltamethrin and cypermethrin (Joseph et al. 2004). It is therefore surprisingly underutilised in pest control. Chimbe and Galley (1996) reported the petroleum extract of the plant material against *Sitophilus oryzae* and *Prostephanus truncatus,* but it was less effective than *Dicoma sessiliflora*. Rotenoids are soluble in this solvent so probably account for the activity.

Bobgunnia madagascariensis (Leguminosae) is reportedly used for protection of stored products from beetles in Zambia and other parts of Southern Africa. There is little scientific evidence to support this, however, despite convincing evidence for its effects against molluscs (Borel and Hostettmann 1987; Kone et al. 2004; Marston et al. 1993). Elsewhere ethyl acetate extracts of

the pods were effective against whiteflies and mosquitoes (Georges et al. 2008; Minjas and Sarda 1986), while its anti-feedant and toxic effects are reported against *Heliothine* moth larvae showed and repellent to termites (Crombie et al. 1971). The activity is most likely caused by the presence of saponins which occur in the pods and bark (Marston et al. 1993; Stevenson et al. 2010) since the only other components found in the pods are highly glycosylated flavonoids which are not biologically active to insects (Stevenson et al. 2010). The presence of these saponins, however, does vary between locations or provenance; thus, elite materials are required for propagation (Sarasan et al. 2011).

The genus *Lippia* (Lamiaceae) is used as a medicinal tea against the symptoms of fever, flu and cold (Viljoen et al. 2005). Because this oral use suggests a low acute toxicity to mammals this species is likely to be a good material for upscaling. Madzimure et al. (2011) reported its activity against cattle ticks, while repellency to mosquitoes has been reported (Lukwa et al. 2009; Omolo et al. 2004). The repellency was reported to be due to essential oils including perillyl alcohol, cis-verbenol, cis-carveol, geraniol, citronellal, perillaldehyde and caryophyllene oxide. Several related species are also known to be effective. For example, *Lippia alba* has been reported to be a potent deterrent to *Tribolium castaneum* with benzyl benzoate, β-myrcene and carvone reported to be responsible for the effects (Caballero-Gallardo et al. 2011).

5 Conclusion

Pesticidal plants offer a traditional and economically viable and effective alternative to pesticides for the control of insect pests in stored products. Much research in the last decade has increased our knowledge about new materials and some details about mechanisms of activity, and this work should focus on fewer effective species to develop improved use. However, to enable the uptake and facilitate wide adoption, several aspects of the sector need to be developed. An evaluation of science and technology policies towards pesticidal plants needs to be conducted through multi-stakeholder networks on pesticidal plants. This should provide clear policy guidelines outlining opportunities and hurdles to upscaling the use of optimised pesticidal plant technologies in stored products.

Sustainable production of plant pesticides through commercialised propagation and cultivation needs promotion and scientific support particularly with the selection of elite propagating material. Scientists and nursery growers need to be trained in propagation and innovative application protocols for indigenous pesticidal trees and shrubs while optimising chemical consistency for established species such as Pyrethrum. Harvesting protocols and optimised preparations are required with clear guidelines on which insects certain plants are effective against. Without strong guidance, assumptions about efficacies can lead to ineffective use.

Science and technology innovations for safer and more effective application of pesticidal plants need to be developed and promoted to farmers. Elite materials need to be identified through analysis and biological evaluations, while application procedures need to be developed and promoted to farmers along with safe handling guidance. Finally scientific networks need to work together to ensure that as broad a skill base is in place to drive the research forward.

Pesticidal plants have been an important part of traditional pest management practice by farmers in Africa. We believe they should remain so and be made available as widely as possible. To ensure a future for pesticidal plants, the many bottlenecks need to be addressed by the scientific community, policy makers and institutions involved in research and implementation. Better information is needed to explain how plants work, which pests are appropriate targets and how variability may be overcome with respect to season, locality or variety and best practice for harvesting and application. Furthermore, scientists need to engage with policy makers to tackle conservation issues. If African Governments wish to see the widespread use of pesticidal plants, they need to be encouraged through policy. A strong future for indigenous knowledge

and use of pesticidal plants in Africa will need policy changes to be made to current regulatory frameworks. Scientists and policy makers must work together for safety and to develop simple reasonably priced regulation, particularly for plants already being widely used. Improving our knowledge on variability of efficacy, conservation and regulation remains the big challenge, but we are sure this will increase farmer use and ultimately improve livelihoods through improved food security.

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