Managing legume pests in sub-Saharan Africa: Challenges and prospects for improving food security and nutrition through agro-ecological intensification

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Executive Summary

Pest management technology has been through a number of advances that have, perhaps, moved away from the mass extermination of pests achieved through the advent of synthetic chemicals in the latter half of the 20th century to more agro-ecologically sensitive innovations that attempt to regulate pest populations by interfering with their breeding, attracting predators or repelling the pests from crops whilst attracting them to other plants. However, pest management is more than technology innovations and must enable integration of technologies in a practical and cost-beneficial manner. This paper summarises existing and cutting edge technologies for pest management in the context of legume production in Africa highlighting where advances can be made to improve pest management at the smallholder level. Challenges and opportunities are highlighted, and priorities for research are recommended that complement agro-ecological intensification (AEI). AEI describes the sustainable increase in agricultural production from the same amount of available land area while reducing the negative environmental impacts of agricultural technology ('Reaping the Benefits' – The Royal Society, 2009; Green Food Report - Defra, 2011; 'Sustainable Intensification' - Montpellier Report, 2013). AEI aims to harness knowledge of ecological processes to increase food production and improve livelihoods and challenges global agriculture to achieve a doubling in world food production while sustaining the environment in which we live.

Synthetics are relatively cheap and provide proven pest control. They are substantially underutilised in Africa and could lead to significant productivity increases if their usage could be increased to levels found in other regions of the world. Challenges and opportunities to increased uptake are

- Monetary cost to small holder farmers – cost-benefit not clear when produce is typically not sold or when market values are marginal
- Limited end user knowledge on how to use synthetics leads to excessive use, reduced cost-benefit and subsequent environmental and safety hazards, under-dosing and resistance development, use of wrong pesticide for crop and pest, high poisoning rates to users and consumers
- Poor regulation leads to adulteration, dumping, limited availability, repackaging without labelling

Pesticidal plants are cheap, generally only requiring labour to collect and process, and fit well within IPM and AEI strategies. Most African farmers are familiar with botanicals, but usage is constrained by a number of factors related to gaps in research and development and how they are regulated. Challenges and opportunities to uptake are

- Although generally low-risk, safety data are lacking.
- Hundreds of plant species have been evaluated for efficacy, factors influencing reliability of efficacy are unknown, e.g. that influence the production of bioactive constituents (altitude, season, soil type), that effect the amount of bioactive compounds extracted (solubility, volatility) or the duration/level of control to be expected for different pest species.
- A high level of knowledge is required to use pesticidal plants (when/where to harvest, how to prepare/extract) although much of this may already be known
- Availability of sufficient plants can be limited and/or unreliable due to over-collection, unsustainable collection or competing uses (medicine, fodder, food, fibre) as well as poor propagation properties or habitat conservation
- Regulatory frameworks treat pesticidal plants in the same way as synthetics, and high registration costs of existing systems prevent developing products which cannot be protected by patent making it difficult to invest in registration costs
- Complex chemistry makes registration of products difficult
- Variability in efficacy is a limiting factor but can be managed by selection of effective provenances for propagation

Biopesticides are highly appropriate for IPM and AEI of legume crop production. Several products exist that could contribute to improved legume production in Africa. Challenges and opportunities to uptake are

- The cost of products generally puts them out of reach of small holder farmers
- Shelf life of products is often limited, requiring relatively sophisticated marketing chains to improve delivery of high quality products
- Cost-benefits not clear due to input price vs. potential income or gain in food security/nutrition

- Research and development is focussed on servicing developed country needs, often advanced technology/knowledge is required to mass produce biopesticides.
- Effects often not immediately evident and pest takes days to control leaving farmers uncertain of their benefits

Biocontrol organisms are highly appropriate for IPM and AEI of legume crop production. Artificial augmentation of predators and parasitoids can work well, but is generally expensive to produce and works best with high value crops in enclosed environments, such as glasshouses, where it is relatively easier to maintain investment and prevent escape of organisms. Augmentation in small holder legume farming systems is probably not cost-beneficial in the short to medium term in Africa. However improving farming practice to improve ecosystem services of natural biocontrol is feasible. Challenges and opportunities to uptake of natural biocontrol are

- More research is required on the alternative crop requirements and optimal environments for predators and parasitoids as it is still not clear how best to optimise predator numbers for key pests or what level of pest control can be achieved
- Increasing end user knowledge on how to improve (engineer) environments that increase predation combined and enhance pollinators
- Understanding costs and benefits of improved biocontrol, particularly when physical inputs are required (e.g. planting/maintaining trap crops or overwintering crops)
- Increasing farmer knowledge on the impact of general farm practices on biocontrol (frequent use of generic synthetic pesticides, field clearing with fire)

Semiochemicals are highly appropriate for IPM and AEI of legume crop production. Pheromone traps can be cost-effective for monitoring important pests like army worm or pod borer, particularly if implemented at the community level. The cost-benefits of pheromones to manage pest populations (through mating disruption or removal trapping) is less clear and currently only works for some key pests of high value crops. The use of naturally released semiochemicals through push-pull cropping strategies has been shown to be highly beneficial for reducing key maize pests in smallholder farming. Despite this, evidence of uptake by African farmers has been limited even when heavily promoted through intensive knowledge training programmes. Challenges and opportunities to uptake are

- The cost of products generally puts them out of reach of smallholder farmers
- Efficacy may be limited
- Knowledge to use effectively is high

Resistance mechanisms are arguably the most effective method for delivering improved pest management to small holder farmers. Farmers may have to buy seed, but then often don't need to make any further inputs to receive benefits of lower pest problems. If non-hybrid resistant varieties are developed, farmers can self-propagate the crop for many years. Challenges and opportunities to uptake are

- The costs of developing new varieties is coming down through the use of gene marker technologies; however, developing resistant varieties still requires a significant research investment, often supported by the public sector.
- Adding resistance often means enhancing the natural production of detrimental compounds with in the plant, which may have effects on consumer health and safety and/or pollinators/ecosystem services.
- The cost-benefits may be high for farmers, but if adding in the R&D investment, it is not clear whether overall cost-benefits to society are positive, particularly if insects rapidly adapt to resistance mechanisms requiring further investment in varietal development.
- Some of the more rapid methods of resistance breeding, e.g. genetic modification, remain controversial

The development of strategies to enhance agro-ecosystem resilience is by definition an integral part of IPM and AEI in legume production. In many cases farmers already employ traditional practices which improve agroecosystem resilience. Frequently, the practices do not require expensive inputs or elaborate technology. Challenges and opportunities to uptake are

- The strategies may be multi-facetted and complex with diverse objectives rather than being a more tangible single technology directed at a specific problem. This impinges on issues of training and clarity in what is being offered
- Strategies tend to be beneficial to the health of the agro-ecosystem in general (soils, nutrition, water, pollination) but often have limited direct effect on pests
- Conflicts may exist between objectives so, for example, use of green manure while having advantages for soil, nutrition and water, can also increase soil pest problems
- Perhaps more than other approaches, agro-ecosystem resilience strategies are not 'one size fits all', and must be tailored to local conditions, e.g. appropriate intercropping strategies are dependent on the cropping system and culinary context
- Some strategies, e.g. incorporation of areas of natural vegetation in the agro-ecosystem landscape, require implementation of wide geographical scales in order to achieve most benefit

Agroecological pest management by small holder farmers in Africa requires building substantial understanding of crop-pest-environmental interactions, which requires investment in training by institutions and farmers. This presents certain challenges and opportunities:

- Farmer field school approaches are well developed in many parts of Africa and have been successfully used in Asia to develop capacity for agroecological pest management. The experience in Africa has been that only a limited number of farmers invest in building agroecological reasoning into their management, but FFS have been effective in promoting farmer to farmer technology transfer.
- Agroecological knowledge based pest management has been more successful in higher value crops, with complex pest problems, and where use of pesticides may be limited by regulation or have limited effectiveness.
- Research and validation is required is develop discovery-based learning approaches that will enable farmers to take informed decisions needed for agroecological pest management.

Recommendations

Although some legume pests are cosmopolitan, many are crop and location specific, such that African farmers are faced with their own unique pest complexes and production issues. Prioritising legume crops (both popular and less popularly grown) and their key pest problems has not been systematically carried out for African regions. With limited resources for research and development, there is merit in bringing together key stakeholders to discuss and assess the existing evidence of pest impacts, pests that are potentially neglected in terms of scientific understanding and developing categorical priorities for legume pest management research and development. Regional workshops involving researchers, farmers, government and private sector stakeholders could help focus legume pest management research priorities based on available evidence.

Improve access to synthetic pesticides by engaging with government, business and NGO stakeholders. This must go hand-in-hand with improved knowledge to smallholder farmers on safe and effective use and improved regulatory frameworks and enforcement of regulations to ensure appropriate products, e.g. small amounts of correct pesticide that are appropriately labelled, reach smallholder farmers.

Pesticidal plants are already used by many smallholder farmers in Africa and they can be an economically viable method to manage pests. However, efficacy is more variable than with synthetic pesticides. More investment in research that is focussed on constraints to uptake and quality control at farm level will improve reliability and the expectations of farmers. Improving access must also consider ways to increase supply and demand of pesticidal plants through development of value chains and multi-stakeholder engagement to improve regulation and registration policies. Pesticidal plants are an appropriate tool for agro-ecological intensification as well as providing one of the cheapest ways of managing pests at the local smallholder level.

Biopesticides and semio-chemical control are currently too expensive, with poorly developed value chains in Africa to meet smallholder farming constraints. More investment in research should be encouraged to develop products that can be locally produced in Africa. Such products would be highly appropriate for integration into agro-ecological intensification programmes in the medium to long term.

Breeding for host plant resistance to insects, diseases and weeds into legume crops has arguably the greatest potential to ensure uptake by smallholder farmers as once in the hands of farmers it requires no further inputs. Resistance breeding is already an important research activity receiving considerable investment by the public sector. However, more investment into research programmes specifically working with smallholder farmers to target crops and pests important for food security and nutrition in Africa could make major productivity gains at the smallholder level. Such programmes should ensure that new technologies that increase the speed of resistance discovery and variety development are at the heart of research investment. Resistance varieties are a key factor in agro-ecological intensification; however, verification of resistance effects on ecosystem services, i.e. pollination and predation, must be considered in addition to potential human health and consumer safety issues.

Improving farming practices and agro-ecosystem resilience that improve ecosystem services, particularly predator and parasitoid numbers, within legume crops can make an important contribution to agro-ecological intensification. However, it is an area of research that is not well developed and is context specific, requiring more research investment to understand fundamental ecological interactions and complexity of interactions. Research from one crop or region may not translate directly to other contexts, and as the majority of existing research has taken place in Europe and North America, it is not clear what lessons can be learned for deploying that knowledge directly in Africa. We recommend more investment in to research that is context-specific to key legume crop species produced in sub-Saharan smallholder environments. Research on true integration of crop production issues, going beyond IPM, i.e. not only weeds, disease, insects, but also soil nutrients, biodiversity, water, has rarely been carried out and requires investment in research to develop appropriate decision making systems for African legume farming. Investment is unlikely by the commercial sector and the returns on public sector investment must be considered in the medium to long term. Immediate gains from small-scale research investments are likely to be limited. Farmer training in good agro-ecosystem husbandry is likely to be a key part of facilitating advances in agro-ecosystem resilience as the practices cannot be expressed using a simple recipe but require the farmers themselves to apply wide-ranging principles in a very local context.

Improving farmer access to existing pest management knowledge should be a high priority for investment. Many pest management technologies and strategies are known to be effective and have been enthusiastically adopted by some smallholder farmers. Because productivity is relatively low in Africa, many gains in pest management can be made through more efficient use of synthetic pesticides and pesticidal plants, improving plant resilience to pests through better soil nutrients, weeding, predation etc. Much public sector investment is already made in FFS and other knowledge dissemination programmes for smallholder farmers in Africa. However, there is still no strong consensus on methodology and the level of knowledge to transfer. Pest management, particularly if wishing to move towards IPM and AEI, requires farmers to have more sophisticated knowledge and decision making tools. For a given investment, developing and delivering curricula must have tradeoffs between number of farmers trained and the depth of knowledge provided. However, significant knowledge gains can be made through “trickle down” approaches that reach many farmers with limited knowledge delivery, or with “experiential” approaches that reach fewer farmers but provide more sophisticated knowledge. Both approaches are valid and arguably take as long (and cost as much) to provide the same number of farmers with the sophisticated knowledge required for IPM and AEI decision making. Measuring the cost-benefits of investment in knowledge provision must take a broad analysis that goes beyond improvement in crop yield and accounts for enhanced food security, nutrition, environmental protection and consumer safety.

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Introduction

Pest management technology has been through a number of advances that have, perhaps, moved away from the mass extermination of pests achieved through the advent of synthetic chemicals in the latter half of the 20th century to more agro-ecologically sensitive innovations that attempt to regulate pest populations by interfering with their breeding, attracting predators or repelling the pests from crops whilst attracting them to other plants. However, pest management is more than technology innovations and must enable integration of technologies in a practical and cost-beneficial manner. This paper summarises existing and cutting edge technologies for pest management in the context of legume production in Africa highlighting where advances can be made to improve pest management at the smallholder level. Not all aspects of pests in legume production are discussed, excluding post-harvest insect pests and non-insect pests (nematodes, weeds, bacteria, viruses) in order to focus solely on insect pest problems during legume production. Challenges and opportunities are highlighted, and priorities for research are recommended that complement agro-ecological intensification (AEI). AEI describes the sustainable increase in agricultural production from the same amount of available land area while reducing the negative environmental impacts of agricultural technology ('Reaping the Benefits' – The Royal Society, 2009; Green Food Report - Defra, 2011; 'Sustainable Intensification' - Montpellier Report, 2013). AEI aims to harness knowledge of ecological processes to increase food production and improve livelihoods and challenges global agriculture to achieve a doubling in world food production while sustaining the environment in which we live.

Despite many technological advances and improvements, pest management continues to be a major constraint to crop production. New pests emerge through invasion, secondary pests become more problematic due to control of primary pests, and pests develop physiological and behavioural resistance to control strategies. More variable weather can make pest outbreaks more unpredictable and/or severe and often the scaling up of production via higher yielding varieties, more intensive production or through the increase in land area planted leads to more persistent pest problems. Smarter, better and more integrated pest control that improves quality and quantity of crop production for less cost is something that both farmers and society desire. However, determining the costs and benefits of pest control and balancing individual, societal and environmental costs and benefits is not easy. Farmers want pest management that requires minimal labour and financial inputs whilst maximising yield. Although farmers do not want to damage the environment, their actions may be uninformed and cause inadvertent excessive damage to the environment and society. Trade-offs between food security, nutrition, environmental protection and food safety must be rationally considered, and improving the application of pest management must be an important part of global efforts to produce more nutritious food from less land without excessive damage to ecosystem services. Realising agro-ecological intensification of legume crop production in Africa and elsewhere requires a re-assessment of pest management, looking at current/potential options and how future research, specifically focussed on legume production in Africa, should be structured.

Traditional African agriculture is characterised by a large number of smallholdings of no more than one hectare per household. Crop production takes place under variable agro-ecological conditions, with annual rainfall ranging from 100 - 800 mm in Savannah/Sahel regions, to 1500 to 4000 mm in forested regions. Increased population pressure and the resulting demand for increased crop production in Africa have necessitated agricultural expansion with the concomitant decline in overall biodiversity. At present, about two dozen arthropod pests, both introduced and native, are recognized as one of the major constraints to agricultural production and productivity in Africa. Although major yield losses have been observed, the economic significance of the majority of pests under farmers' production conditions is not adequately understood. Socio-economic constraints have kept pesticide use in Africa the lowest among all the world regions. The bulk of pesticides are applied mostly against pests of commercial crops such as cotton, vegetables, coffee, and cocoa, and to some extent for combating outbreaks of migratory pests such as army worm and locusts. Many pest management research activities carried out in Africa have not been widely adopted. This could be due to African farmers facing heterogeneous conditions, and needing a variety of options to choose from instead of fixed prescriptions. Pest management knowledge is often site-specific and should be the basis for developing integrated pest management (IPM) techniques. Farmers often lack the biological and ecological information necessary to develop better pest management through experimentation. Formal research should be instrumental in providing the input necessary to facilitate participatory technology development such as that done by Farmer Field Schools, an approach emerging in different parts of Africa.

Legume pest control tools and strategies

Integrated pest management (IPM) is the internationally recognized approach to pest and disease control which has been practiced for well over 50 years. All farmers practise IPM to some degree. However, challenges in increasing adoption are largely due to the need to increase farmers' knowledge and because no single IPM strategy can be recommended, dependent on crop, scale, location, available inputs and market values. Thus, while training manuals can be developed to provide guidance on best practice in IPM they would need to be tested and validated under local conditions. Best practice will be dependent on scale and available resources, and, for example, IPM recommendations in the context of small holder cowpea production in Africa will fundamentally differ from IPM within large scale mechanised production of soybeans in Brazil.

Synthetic chemicals

Most African farmers do virtually nothing to control pests. Small holder legume production in Africa is, by default, largely organically produced. The typical farmer in Africa does not buy fertiliser or other chemical inputs and relies on human/animal labour for soil preparation and weeding, often making very minimal crop management inputs as a means of risk management. If farmers do anything about insect pests, it usually involves buying a commercially available synthetic pesticide when severe problems are noted.

The advantages and disadvantages of synthetic pesticides have been assessed and reviewed by many experts (Bennett et al 2010; Cooper and Dobson 2007; Atreya 2006). Synthetics have undeniably been responsible for major improvements in pest management and increasing crop yields across the globe. However, Africa accounts for a very small percentage of the global pesticide market (Fig 1). African countries with rapidly expanding agricultural export industries, e.g. South Africa and Ghana, are the main users of pesticides in Africa (Fig 2). The benefits of synthetic use to increase food production, as has occurred in other regions of the world, indicates there is much potential to improve food production in Africa by promoting pesticide use (Cooper and Dobson 2007). Advocating increased use of pesticides will seem controversial to many, particularly as the focus of recent research in developed countries has increasingly been on the detrimental effects of pesticides, often losing sight of balanced, unbiased cost-benefit analyses of pesticide use. Expanding the use of synthetics in Africa should be appropriately contextualised with regards to the different priorities and problems related to food security, nutrition and health that exist between developed and developing countries, and the general trends within pesticide development and regulatory frameworks that are increasing the safe use of synthetic products. Of course, there are many problems with the use of pesticides in Africa, e.g. adulteration, using the wrong pesticide, using too much/little pesticide and the relatively larger number of farmers using pesticides at the small scale. However, better education and regulation should be seen as the correct solution, instead of banning/removing pesticides. Important challenges remain for African regulators and policy makers to improve access to and knowledge about synthetic pesticides.

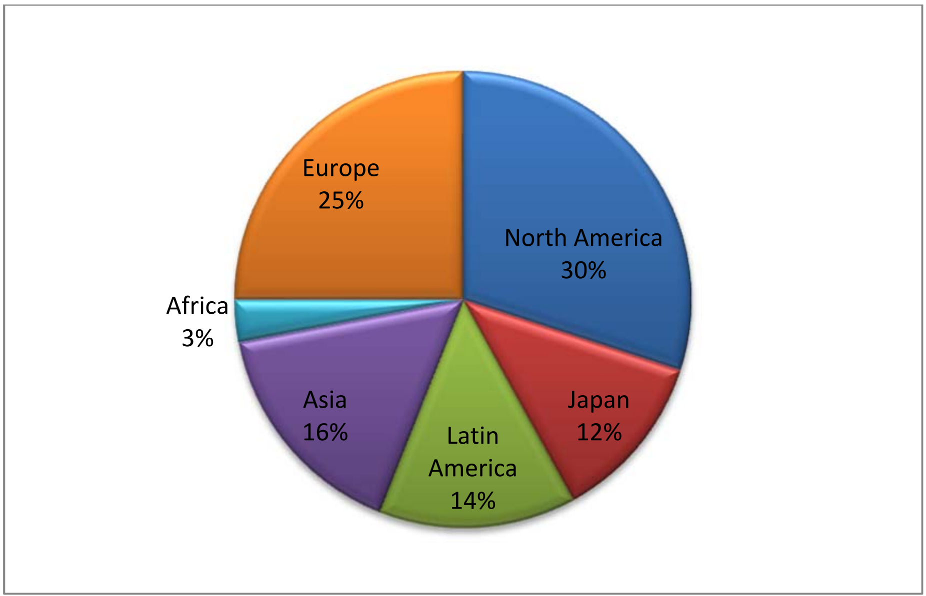

Figure 1: Regional use of pesticides, 2010 data. Source: FAOSTAT

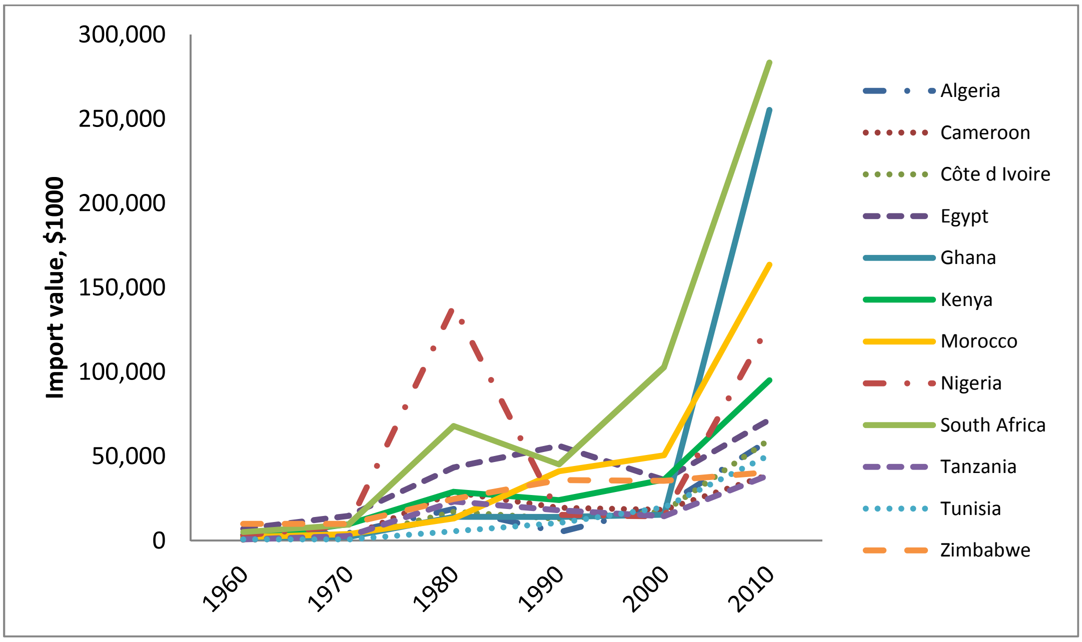

Figure 2: Commercial pesticide import levels of 12 countries in Africa accounts for 80% of all pesticide use in Africa (2010 data for 57 countries). Source: FAOSTAT

Synthetics for improved legume production

Pesticide use has typically been minimal on smallholder legume production, partly due to cash flow constraints, limited availability and low levels of information on synthetic products and cost-benefits of their use. There is a limited amount of published data on the efficacy of pesticides for pest and disease control on small scale legumes in Africa. Cork et al (2009) provides the best general overview of research carried out within Africa, as well as elsewhere, on the contribution of synthetic pesticides to pest management within legume production. The majority of the published research cited by Cork et al (2009) looks at the benefits of synthetic use on various target pest species, particularly *Maruca* spp, *Aphis* spp. and *Megalurothrips* spp. and subsequent changes in productivity achieved when using synthetics in different contexts, combinations or localities. Certainly many gaps in research remain with respect to synthetic use, particularly in the context of their integration into IPM and their efficacy against emerging/difficult-to-control pests. General conclusions of the existing body of research indicate that significant gains in yield can be achieved by carefully timed decision-based spray applications. So although the economics, availability and limited capacity and reliable information has meant that pesticides have not been used extensively on small-scale legume production in Africa, there is enough published information and experience with other crops to suggest the cost-benefit ratio of controlling pests and diseases using pesticides is favourable if they are applied to a high standard of timing, dosing and targeting as part of an IPM strategy. The developed-world movement to reduce, restrict and remove pesticides from crop production is not entirely applicable or beneficial for Africa, where farmers actually need increased access to synthetics as well as much better information on their safe and effective use.

Pesticidal plants

Pesticidal plants contain a mixture of bioactive compounds that have many advantages in terms of efficacy and preventing the development of insect resistance when compared to synthetic pesticides. However, fundamentally pesticidal plants are similar to synthetics in that they contain toxic compounds and, thus, safety to users and consumers must be considered when officially recommending pesticidal plants for pest control. However, pesticidal plants are typically applied in ways that minimise safety concerns. The active ingredients may be extracted in water and sprayed on crops, but there is rarely any effort by the farmer to concentrate the active ingredients to higher levels than that found naturally in the growing plant. For example, the WHO classifies rotenone as moderately toxic with equivalent acute mammalian toxicity to many currently accepted products including pyrethroids. Rotenone is thought to have an oral lethal dose of between 300 to 500 mg/kg in humans. Thus, plant material with a total rotenoid content in dry leaf of around 1% by weight and assuming all rotenoids are equally toxic to rotenone (although most are considered less toxic such as the deguelin and tephrosin found in *Tephrosia vogelii* (Stevenson et al 2012; Belmain et al 2012)), a 70kg human would need to consume more than 2kg of dry plant material in one sitting. Thus exposure to plant material at concentrations typically used by African farmers is in reality unlikely to present dangers to users, particularly when put in context to the highly purified and concentrated synthetic products that are currently used. The compounds found in pesticidal plants are often susceptible to degradation by sunlight or oxidation and typically do not last long after application, particularly when compared to synthetics which have been designed to be more stable and contain adjuvants to prevent their rapid breakdown. Furthermore, the compounds present in pesticidal plants are often not fast acting nerve toxins in the way that most synthetics rely on acetylcholinesterase inhibitors. The compounds present in plants are more likely acting as feeding deterrents, repellents or interfering with insect development, i.e. generally acting through pathways not found in non-target organisms. So it is important not to lose perspective in assessments of harm to human health when using pesticidal plants. The renowned physician, Paracelsus, wrote in 1536 that "Poison is in everything, and no thing is without poison. The dosage makes it either a poison or a remedy." (Paracelus 1536). This principle should not be lost sight of when considering using plant materials for pest control because the amount of active ingredient used is often very low.

Plant materials are known by farmers to be environmentally benign, safer and cost-effective compared to synthetic pesticides (Kamanula et al 2011) as well as being difficult to adulterate when produced or harvested by farmers, themselves. According to recent surveys in Malawi and Zambia (Nyirenda et al 2011), farmers favour plant materials as environmentally benign, safer and more cost effective than synthetic pesticides and recognize pesticidal plants as reliable, and if collected or produced themselves, that their cost can be calculated in terms of time rather than in cash. Many farmers already use pesticidal plants but report the need for research to improve their use. Their cost to farmers is substantially lower than synthetic products and can be calculated simply in terms of time to harvest and process. Generations of farmers have used plants in this way, making the technology familiar, trusted and acceptable. However, their priority in agricultural policy is low. This is due to knowledge gaps as well as the fact there are few commercial incentives or revenues to drive policy and uptake as is the case with commercial synthetic pesticides. Successful commercialisation has been achieved for some products such as Pyrethrum and Neem (Isman 2006). However, owing to the cost of registration, even Pyrethrum products in countries where it is produced, e.g. Kenya and Tanzania, are registered for relatively few domestic uses, and Pyrethrum is rarely used by farmers who grow it. The various constraints that hinder the large-scale uptake of pesticidal plants have been expertly reviewed (Isman 2008), highlighting that Africa is the place with the most to gain by building a pesticidal plant value chain based on existing indigenous use.

Opportunities to further develop and promote promising pesticidal plant species require more research to see how well they can work under different farming practices, in different locations, in different crop types and against different crop pests. Such research may seem "never ending" but is essential to inform/improve on existing farmer practice and deliver technologies that are more readily integrated into agro-ecological intensification programmes when compared to broad spectrum synthetic pesticides. Much previous research on pesticidal plants is largely confined to trials aimed at demonstrating efficacy against various target species under laboratory conditions. What has normally been lacking is more detailed study on the chemistry (active constituents, variation, solubility), mode of action (toxic, repellent, antifeedant) and practical evaluation under farm field conditions, replicated over seasons. The existing body of research has not gone far enough to deal with the constraints that are responsible for preventing uptake of pesticidal plants. Many farmers would use pesticidal plants if they were locally more abundant via local propagation/conservation and/or markets. Despite large amounts of research, questions of efficacy and safety remain due to lack of focus on key constraints. There are few existing commercial incentives to develop pesticidal plants as occurs with synthetic products. With synthetics, commercial companies know they can afford the data registration costs because their compound can generically kill many insect species around the world, can be delivered through existing marketing chains and can be protected from competition to regain the costs of development and registration. Pesticidal plants will never be as generically toxic in their efficacy, with smaller numbers of uses and not easily protected with a patent unless formulated.

Thus alongside research, it is important to engage with existing and potential businesses involved in the supply of indigenous medicines, natural remedies and wild foods/spices in order to develop value chains for pesticidal plants and work with African regulators to adapt pesticide policies that currently inhibit registration of natural pesticide products. Although farmers continue to use pesticidal plants under their own initiative, it is not possible to formally promote them because they are not available as registered products for sale (due to the high costs to supply safety and efficacy data in comparison to the likely profits derived from an unpatentable product). Developing natural pesticide value chains in Africa could free African farming and governments from the expensive importation of synthetics. Pesticide importation contributes to trade imbalance, promotes dependency, waste dumping and inhibits the development of national/regional value chains for locally produced pest management technologies. Across Asia, many countries are redesigning their policies to encourage biopesticide technologies and developing small enterprises (Leng et al 2011). Africa has the fastest growing problem in human synthetic pesticide poisonings (Konradsen 2007) with untold damage to the environment happening particularly from disposing of old/banned stockpiles of synthetics (http://www.fao.org/agriculture/crops/obsolete-pesticides/africa-program/en/). Until now, investment costs in developing pesticidal plants have largely been met by the public sector. The commercial sector can deliver products more effectively but simply cannot compete within the same regulatory framework developed for more toxic synthetic products. Changes in policy are possible that can kick-start business development of pesticidal plant value chains as has occurred in China, India and elsewhere in Asia, but the process needs to be championed by working with stakeholders to create change in Africa.

Micro-biological control

Biological pesticides, or biopesticides, typically refer to the use of living organisms to kill pests. In the broadest sense, some experts include predators and parasitoids in this definition. However, more often the term biopesticide is specifically used to describe the use of entomopathic fungi, bacteria and viruses which are commercially produced and formulated into liquids or dusts that can be sprayed on to crops in a similar way to the application of synthetic chemical pesticides. When discussing biological control, it makes sense to divide this topic into micro-biologicals (disease causing organisms) and macro-biologicals (predators, parasitoids), which fundamentally differ in their production and application in crop protection.

Microbiological control has many advantages over the use of chemical control (synthetic or pesticidal plants) because the agent can self-replicate and spread, with the potential for longer lasting effects over time and space. Most entomopathic micro-organisms are highly specific to groups of insect species, often making them very compatible with macro-biological control, IPM strategies and human health and food safety. Generally, they leave no toxic residues on treated plants and are not harmful if inadvertently ingested. Most countries have developed new registration protocols to deal with the use of biopesticides, and their simplified registration has led to many new products entering the crop protection market. However, biopesticides are still a small, albeit rapidly growing, part of the commercial market for pest control. A study released by Global Industry Analysts, Inc. estimated that biopesticides represented about 3% ($750 million) of the overall pesticides market in 2008 and was likely to reach the $2.8 billion by 2015 (GIA 2012). In addition to relatively favourable regulatory frameworks, changes in technology have made it possible to mass produce many micro-organisms more cheaply than before, bringing prices closer to that of commercial synthetic pesticides.

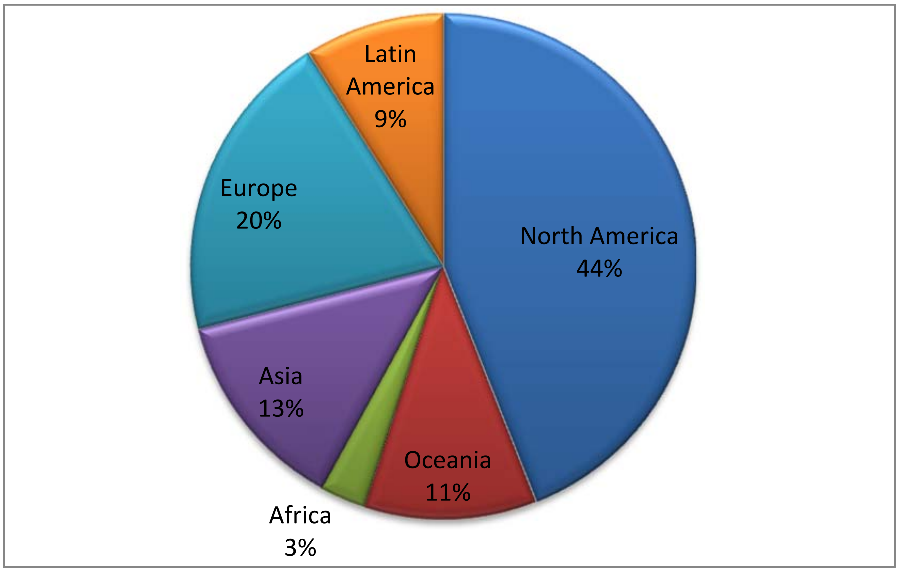

Figure 3: Regional use of biopesticides, 2010 data. Source: AGROW

Biopesticides for improved legume production

Lepidopteran pests continue to be one of the main targets of microbiological products, and key pests of legumes grown in Africa that could be amenable to effective microbial control include *Maruca vitrata* on cowpea, *Spodoptera litura* on groundnut and *Helicoverpa armigera* on chickpea. These pests could be controlled with either Bt (*Bacillus thuringiensis*) or NPV (nucleopolyhedroviruses) (Lingappa & Hegde 2001). Some sucking pests such as pod suckers, e.g. *Clavigralla tomentosicollis*, and thrips, e.g. *Megalurothrips sjostedti*, as well as egg stages of other pests, may be susceptible to control with entomopathogenic fungi. Some bacterial and fungal products have been tailored to other insect groups and could be useful for pests such as bean stem maggot. Todd et al (2010) currently provides the most comprehensive global review about biopesticides, particularly with reference to their use and regulation. More African-focussed reviews can be found in Grzywacz et al (2009) and Cork et al (2009). While the technical constraints to developing and scaling up microbial control of some key legume pests are not great, the limited capacity in applied research, production and registration in Africa as well as the high costs of using microbials on smallholder farming systems, in particular, do not make microbial control currently a viable option in the near future unless these capacity issues are addressed and even cheaper production models developed.

Macro-biological control

Biological control with natural enemies can be employed through two general strategies: 1) artificial augmentation of natural enemies and 2) encouragement of natural populations. Artificial augmentation involves rearing predators at a commercial scale and releasing them on to a crop where the host pest insects are present. This is typically used in glasshouse environments, where it can be quite effective, but tends to be used in high value crops where there is no tolerance for pesticide residues or visual damage. Artificial augmentation is less practical in outdoor field crops and unlikely to be cost-beneficial for small holder farming systems. Naturally increasing the numbers of predators and parasitoids in the environment is possible. Simple strategies such as reducing frequency of synthetic pesticides and carefully targeting pesticide use can minimise impacts on natural enemy populations. Encouraging alternate host plants in the nearby environment can be effective, e.g. flowering plants that provide food such as nectar and pollen for adult hymenopteran parasitoids whilst searching for oviposition sites or wild plants that ensure the availability food on which the immature pest insect develops, thus maintaining/growing the natural enemy populations. Wyckhuys et al (2013) argues that much more research in developing countries is required to implement biological control for agriculture in the developing world, highlighting most research of this nature is focussed in North America and Europe.

Considerable research has been undertaken to identify predators and parasitoids of the most common legume pests. Reviews of natural enemies on cowpea can be found in Fatokun et al (2002) and Singh et al (1997). Natural enemies on chickpea, pigeonpea, groundnut and soybean can be found in Upadhyay et al (2009). Rates of parasitism and predation can vary quite considerably, but there is no doubt that such biological control can help regulate pest numbers in many situations. Natural enemies and parasitoids of *M. vitrata* have been extensively studied, and although parasitism is typically less than 50%, the egg parasitoid, *Trichogrammatoidea eldanae*, is thought to have value for control of *M. vitrata*. The larval parasitoid *Ceranisus menes* has shown promise in the control of flower thrips *Megalurothrips sjostedti* in West Africa. *Bracon hebetor* has been found to attack *M. vitrata* in India, highlighting that there can be considerable regional variation in species attacking more cosmopolitan pests. More regional research in Africa to understand alternate host plants for different natural enemies attacking legume crop pests is most certainly required as well as how such plants can be encouraged/grown as part of strategies aimed at increasing biological control (Wyckhuys et al 2013). In addition to such ecological research to understand best practice yield improvement through biological control, socio-economic research on the cost-benefits to smallholders will be essential to understand whether additional efforts to maintain alternate host plants and natural enemies is, indeed, beneficial.

Semiochemical control

Semiochemicals are chemicals that act as messengers as a form of communication between individuals of the same species, e.g. sex pheromones, aggregation pheromones, or to send messages to other species, e.g. allelochemicals produced by a plant that attract predators of an insect feeding on that plant. Their use in crop protection can take many forms both in monitoring for the presence of pests as well as to help reduce pest populations. Sex pheromones are usually produced by either the male or female of a given species and can be an effective way to monitor for the presence/absence of the pest. Identification and synthesis of such compounds and incorporation in to slow-release lures has become a well-established area of research and commercial development. Using pheromones for monitoring can be a cheap and easy way to assist decision making of when to take further action to control pests, e.g. with pesticide when the numbers of insects trapped reaches a certain level. Sex pheromones have been identified for key legume insect pests, notably *S. exempta*, *H. armigera* and *M. vitrata* (Schulz, 2004). Although not fully optimised, the pheromone of *M. vitrata* has been successfully disseminated to farmers in Benin for use as an early warning tool. Probably the best known pheromone monitoring network is that for the African armyworm, *Spodoptera exempta*, with pheromone traps used to track its migration from Tanzania to Ethiopia. The data collected has considerable predictive value when linked to weather forecasts allowing risk of outbreaks to be measured and early warnings released to farming communities.

If pheromone-laced traps are placed in abundance, they can have effects on populations by trapping out large numbers of the pest or through disrupting the mating process, i.e. flooding the environment with the odour such that the sexes cannot locate each other. Using pheromones in this way is considerably more expensive as many more trap/lures are required. Such control strategies have been developed from some important pests found on high value crops, but as of yet, have not been developed for specific legume pests.

More recent research in the field of chemical ecology has focussed on understanding crop production systems that utilise naturally-produced allelochemicals (http://www.push-pull.net/). Push-pull cultivation of maize that involves the intercropping of plants that are attractive and repellent has been shown to be effective in pushing stem borers away from maize plants whilst pulling the insects towards an attractive trap crop (Khan et al 2010; Hassanali et al 2008). Likewise some researchers are developing ways to exploit plants under insect attack that release alarm compounds which stimulate the defences of neighbouring plants and/or recruit predators/parasitoids in tritrophic interactions (Vandermoten et al 2012).

Making it more difficult for pests to find their host plants is one of the motives behind intercropping. Many legumes are intercropped with cereals, often to improve nitrogen availability to cereals, but it is also argued to help reduce pest damage. However, this is not necessarily the case and depends on the intercropping species and pest complex since the micro-climate created can actually increase pest and disease problems for legumes (Jackai and Adalla 1997). Getting the right mixtures of plants together needs to consider not only the chemical ecology of pests, but dynamics affecting competition for nutrients, sunlight and water that could have larger effects on yield in comparison to mono-cropping. See below section about agro-ecosystem resilience for more information on intercropping effects.

Using semiochemicals for pest control is a very promising field of research with some real products already delivered and in use. So far, however, the costs of research and development and implementation costs have limited semio-chemistry to ubiquitous pests affecting high value crops in developed countries. With continued research that is appropriately focussed, there is much scope to develop technologies that could be appropriate for legume pest management, strategies that would be particularly suitable for agro-ecological intensification. Feasibility of implementing semio-chemical strategies by smallholder farmers certainly requires socio-economic assessment as even where the cost-benefits of push-pull have been demonstrated in Africa and intensive FFS implemented, uptake by farmers has often been very limited.

Resistance in legumes

What is host plant resistance?

Plants are exposed to predation by herbivores, diseases, nematodes and parasitic weeds. As a consequence of this damage and death, they have evolved mechanisms to withstand these biological threats to their survival. Through millennia of targeted selection for yield and other favourable food qualities (flavour, colour, shape) mankind has effectively bred out many of these natural defence mechanisms from cultivated species of plants leaving most crops highly susceptible to damage from these biological constraints. Phenotypic expression of defence that still occurs in crops is called host plant resistance (HPR) and under ideal circumstances presents perhaps the best solution to pest and pathogen control. This is because HPR is, in the main, environmentally benign, is inherent and heritable and pests or diseases are less likely to overcome natural defence mechanisms than for example synthetic chemicals or foreign components from biological sources such as Bt toxin because HPR have evolved rather than been contrived. In practice, it's not that simple and decades of research on resistance have still not resolved pest and disease problems in most crops, including legumes. However, there are examples where host plant resistance provides effective control of pests or diseases and is used on farm.

As our ability to manipulate genes and tag phenotypic characters improves so our ability to exploit resistance increases. In terms of crop protection, HPR represents the inherent ability of crop plants to restrict, retard or overcome pest/pathogen infestations and thereby reduce yield loss and/or improve quality of the harvestable crop product.

The effects on host plants, and HPR, vary according to the nature of the pest. While no single overarching system of description will provide comprehensive cover for all mechanisms, resistance to arthropods is traditionally described according to three groupings based on how they are expressed or how they affect the target organism – tolerance, anti-xenosis and antibiosis.

Arthropod pest resistance

Tolerance is typically a polygenic trait enabling a plant to withstand or recover from infestation by an insect or the extent to which a plant can support an insect population without loss of vigour or crop yield.

Anti-xenosis describes what is alternatively called non-preference in which a plant trait presents a chemical or biophysical barrier that is deterrent or repellent to the arthropod. The pest chooses to move away but remains unaffected. This may have implications for combining with other IPM approaches such as biological control using predators or parasitoids. An insect poisoned by a plant defence chemical may pass that effect on to a predator or parasitoid whereas resistance that dissuades insects may leave them harmlessly exposed to parasitoids by increasing searching time and therefore more exposed to natural enemies e.g. leaf miners, leaf folders, increasing neonate Lepidoptera 'spin off'.

Antibiosis describes a mechanism whereby the plant character has an adverse effect on the arthropod herbivore killing it or making it too sick to further damage or cause yield loss to the plant. Examples of how these effects may fit an IPM approach include: i) by impairing insect development may lengthen life cycle and so expose the insects to natural enemies for longer such as caffeoyl quinic acids in groundnuts (Stevenson et al., 1993); ii) prevent moulting (e.g., Senthil-Nathan et al., 2009) and so increase the opportunities for farmers to catch emerging populations at appropriate developmental stages with biological or synthetic pesticides; iii) may weaken the insects making them more susceptible to the effects of insecticides or natural diseases. Other mechanisms can be described as follows.

Tritrophic interactions Some plants will release a chemical in response to attack by a herbivore and this chemical will attract an appropriate predator or parasitoid. A well-documented example is the parasitoid *Aphidius ervi* which attacks aphids on legumes (Du et al., 1997).

Host plant quality Although not intrinsically a resistance mechanism the quality of host plants can be important determinants of the success of colonising insects especially in terms of fecundity and may have a role to play in understanding the differential performance of insects on different accessions or cultivars of a crop (Awmack and Leather, 2002). Host plant quality affects reproductive strategies and location of sites for oviposition and may change as a consequence of herbivory. The performance and success of the pest may also transfer to the parasitoids and predators and can impact on all system levels. Resistance to diseases are traditionally described as vertical or horizontal.

Vertical resistance is characterised by a differential interaction or gene for gene relationship so there is either colonisation or no colonisation - there is no intermediate situation e.g. nematode resistance in ground nut (Choi et al., 1999; Church et al., 2005). Typically it is controlled by various combinations of major genes which are highly heritable and which show clear cut, discrete segregation in crosses between resistant and susceptible plants. Because simple gene mutations in the pathogen can provide individuals and therefore populations having appropriate combinations of major resistance genes the plant resistance can be overcome and so is unstable. Indeed exposure to host plant resistance can accelerate adaption and genetic change in the host (Arnold et al., 2007). Vertical resistance controls allo-infection (i.e., those that originate away from the host). The more resistance genes there are the less chance there is of a pathogen overcoming the resistance. As the number of resistance genes increases arithmetically the number of paired genes required to overcome resistance increases geometrically. Single gene resistance is easily lost so many resistance genes together are more durable and can be achieved by marker assisted gene pyramiding which is highly suited to self-pollinated crops like legumes (Ye and Smith, 2008).

Horizontal resistance is characterised by a large number of genes contributing to the observed resistance effect with each gene making a small additive contribution to the overall resistance. The ability of host to parasitize is independent of the host's resistance capability so resistance cannot be over overcome with simply mutations. The resistance is quantitatively inherited and involves a ranking relationship across all races or biotypes. Breeding crops for horizontal resistance is easier and does not conflict with yield or quality. Therefore breeding for horizontal resistance will likely be most appropriate for subsistence farmers and the use of resistant cultivars provides the most appropriate means for the management of pests in developing countries overall.

Why is HPR an improvement on synthetic pesticides in Africa?

Host plant resistance is, by definition, effective because it has evolved to prevent plants fatally succumbing to the effects of a biological constraint. In contrast to synthetic pesticides, for example, HPR is not necessarily absolute because it has evolved to enable the plant to produce adequate seed to survive rather than secure all seeds which are often the aim of pest control strategies. Consequently it may not provide the level of control typically expected in large scale commercial agriculture, which may partly explain why resistance hasn't taken such a prominent role in pest and disease management in all crops. However, in the African context the need for *some* (a noticeable or meaningful level of reduced damage) effective control is required – not necessarily the absolute control that is expected in commercial farming systems. So as with plant based pesticides, which are also no competition to synthetic pesticides, HPR is highly suited to small holder farming particularly with respect to legumes because characters are maintained consistently from one generation to the next since most are self-fertile. So once in the hands of the farmers, HPR can be maintained with little or no cost from one season to the next. Some of the biggest production hurdles are presented by viral diseases which are in many cases transmitted by insects so effective insect resistance may be adequate to control the viral disease or may at least be required to reduce exposure of plants to excessive loads of virus which can otherwise mutate and overcome resistance (Naidu et al., et al., 1998). Where resistance is required for an insect to control a disease the resistance may not require total elimination of a pest (e.g., aphid or whitefly) to be effective but simply require shorter feeding periods.

Resistance is self-sustaining. Once established, resistance should require little on-going cost provided the original material provided to a farmer is not an F1 hybrid. In this case subsequent generations could show unmanageable variation in phenotype. In legumes, resistance can be maintained from generation to generation because many of the crop species are self-compatible so pollinate themselves to produce the harvestable seed thus not contaminating the genotype with genes that might compromise the resistance. Some crops that are produced by cloning, e.g. sweet potato, are also well suited to maintaining the resistance locally. Both these attributes make resistance highly suited to small holder farming by providing environmentally benign pest and disease management that is self-sustaining and eliminates cost of pesticides while increasing food security.

Durability may be put at risk if effects are too intense. Because resistance mechanisms do not exert the same selection pressure on pests or pathogens, in most cases they are more durable than typical pesticides, although resistance does break down and needs to be monitored. Indeed, there is evidence that adaptation to host plant resistance predisposes the development of pesticide resistance in generalist herbivores such as *Tetranychus urticae* (Dermauw et al., 2013). The most effective way to be certain a plant is expressing the resistance is to know what the resistance mechanism is, for example, which chemicals are responsible for the effects, and be able to monitor them. Otherwise quantitative trait loci (QTL) can be monitored, although the presence of DNA does not always mean the production of a compound. Many resistance gene loci and linked molecular markers have been identified using genetic linkage mapping and in some cases resistance provides an important contribution to integrated pest management approaches to productions but still owing to the reliance on pesticides it is inadequately exploited. More progress could be achieved through the exploitation of plant and arthropod genomics (Smith and Clement, 2012).

HPR is environmentally benign and inherently safe to humans and livestock. However where resistance mechanisms are expressed in the edible product, they should be considered cautiously. It is a complicating but not surprising coincidence that many of the invertebrate pests of crops consume the same part that humans and livestock consume so there is likelihood that resistance mechanisms will be part of human diet. Proteins occur in some important legume crops that are highly toxic to seed weevils owing to their enzyme inhibiting activity (Schroeder et al., 1995). Humans would suffer the same effects but for the fact that preparation of the beans by cooking denatures these proteins so as to make them harmless once prepared. Similarly, chemicals that are toxic to invertebrates are often toxic to mammals. Some plant chemicals can show mammalian toxicity, so resistance mechanisms that depend upon these chemicals should be promoted cautiously. For example, *Lupinus mutabilis* grain legume, grown in South America and Australia (Caligari et al., 2000; Clements et al., 2008) produces the herbivore defence alkaloid lupanine along with several other derivatives in all plant parts including the edible seeds. The compound reduces insect incidence such as aphids but farmers wash harvested grains in flowing water (mountain streams) sometimes for several days to extract these compounds Gross et al., 1988). A similar approach is used in the preparation of legume *Mucuna pruriens* in East and Sothern Africa because the seed produces L-DOPA in high concentrations (>5% by weight). Seeds are soaked in waters several times to remove the amino acids. One overlooked consequence of the occurrence of insect toxic plant chemicals in all plants parts is that this will include pollen. Recent work on *L. mutabilis* has shown that lupanine in pollen leads to fewer and smaller males – an effect that could have long term consequences for the colony fitness and success (Arnold et al., in review). Some mechanisms of resistance against pathogens are highly efficient in that the production of defence chemicals is localised and produced only in response to infection (Smith, 1996; Grayer and Kokubun, 2001). These chemicals are generally referred to as phytoalexins. There are numerous papers identifying these compounds in legumes that are important in African agriculture but it is important to consider that as plants develop ways to defend themselves, the invading organisms can develop processes for metabolising defence chemistry (Pedras and Ahiahonu, 2005). Induced defence by insect predation is also an increasingly encountered phenomenon, and mechanisms induced by jasmonate may increase parasitisation of herbivores (Thaler, 1999). Due to their relative safety, HPR is an appropriate pest management approach for organic farming and there are additional ecological and environmental benefits (Zehnder et al., 2007). These arise from increased diversity of invertebrate species in the agricultural ecosystems because the reduced use of pesticides, and in turn, this increases ecosystem stability which promotes a more sustainable system that is less detrimental to natural resources (http://ipmworld.umn.edu/chapters/teetes.htm).

Limiting factors holding up wide-scale adoption of resistance

Resistance mechanisms may not have an absolute control effect against a pest or pathogen because naturally it does not require the complete elimination of a pest to survive. The result is less crop damage. However some resistance mechanisms may not be absolute but may provide adequate resistance to completely eradicate a problem. So a resistant mechanism against aphids on groundnuts may not kill aphids but may make them feed for shorter periods which will then reduce the chance of infection by groundnut rosette disease. For some species, there is not always an effective resistance to a target pest. This can be overcome if wild species can be screened but any mechanisms then needs to be transferred. This is now relatively straight forward as our knowledge of the molecular bases for plant resistance to arthropods improves, but it is still problematic with sexually incompatible sources of resistance.

Research into mechanisms can be time consuming and can present a hurdle but it is important to know what the mechanism of resistance is to ensure it is being expressed even if breeding and selection is carried out using genetic tags. It is possible a genetic tag may be present but an environmental or other factor prevents phenotypic expression of the character. Indeed, as a biological process, resistance is susceptible to variation in expression but this can be monitored if the actual mechanism is known. Wild species are excellent sources of useful agricultural characters but may be incompatible with cultivated species for breeding. However there are examples of where wild species can be crossed. For example mechanisms of resistance to groundnuts identified in wild species of *Arachis* (Stevenson et al., 1993) based on the presence of specific chemistry was later used to screen progeny from a cross between a wild and the cultivated species *Arachis hypogea* (Mukherjee, 2000). Breeding and selection is time consuming and expensive but has become much more straightforward with the advent of techniques for mapping resistance characters, and this has been a prominent part of the acceleration in scope for exploiting resistance, particularly in legumes (Kelly et al., 2003). While marker assisted selection (MAS) in breeding programmes has enabled rapid development of resistance to many diseases, the process for insects and abiotic constraints lags behind (Miklas et al., 2006). HPR may be incompatible with other IPM components (e.g., biopesticides/natural enemies).

The investment into research and outreach using legume crops with host plant resistance in Africa is disappointingly low but could be increased and developed. Pigeon pea is a grain legume of considerable importance in South Asia but has potential for much wider uptake in Africa owing to its drought tolerance and high nutrient qualities. While varieties exists with major disease resistance such as wilt other potentially important agronomic traits in both cultivated and wild species remain largely unexploited despite much research on possible resistance mechanisms (Green et al., 2003 & 2006) Sharma et al., 2003). Pigeonpea is presently grown on ~0.8 million Ha in Africa (http://www.icrisat.org/crop-pigeonpea.htm) but there is much scope for popularising pigeonpea as a major legume crop in Africa (Odeny, 2007). *Cicer arietinum* (Chickpea) is another important grain legume of Asia that has much scope for promoting in Southern and Eastern Africa. Currently grown on less than 0.4 million Ha it has been more extensively studied for resistance than pigeonpea. There are also over 40 wild species that provide a wealth of phenotypic traits for disease resistance (Stevenson and Veitch, 1998; Stevenson et al., 1997, Stevenson and Haware, 1999) and crosses between cultivated and susceptible species have been these have been mapped to localize disease resistant genes (Winter et al, 2000). Compounds associated with disease resistance in chickpea have also been shown to be deterrent to important insects pests of chickpeas including the cosmopolitan and polyphagous species Helicoverpa armigera (Simmonds and Stevenson, 2001). *Phaseolus* vulgaris or common bean is an established legume component of African agriculture but is highly susceptible to numerous constraints. Recent examples of resistance research include work on the *Ophiomyia* sp. (bean flies) which are considered to be the most important pests of beans in East Africa. (Ojwang et al., 2010) . *Vigna unguiculata* (cowpea) is also an established legume of African agriculture particularly West Africa but grown widely across the continent. Recent work on resistance mechanisms to *Striga* have been reported above (Timko et al. 2012) but other constraints are also currently under study. For example, Makoi et al., (2010) have shown strong correlations between flavonoids and anthocyanin concentrations in seeds associated with reduced insect crop damage to insect pests of seedlings since these compounds serve as deterrents at seedling stage Ndakidemi and Dakora, 2003.

What can be done to reinvigorate HPR as a tool in resource-poor farming systems?

The two main targets for research should be to determine mechanisms of resistance in crops to insects and diseases and use this information along with biological assays of the comparative effects of organisms colonising or feeding on crops for mapping resistance so that it can be incorporated into preferred genotypes rapidly. Land races and wild relatives provide a rich gene pool of important agronomic traits that can be exploited with the emergence of modern gene mapping techniques and the potential to recombine genes from otherwise incompatible but closely related species. The potential for wild crop relatives has perhaps never been more acute, especially for resistance. Resistance needs to be considered as an effective measure for managing pests and diseases and not necessarily absolute control. The most effective system is likely to be a combination of IPM components (biopesticide/natural enemies) where a significant effect is likely to provide an adequate additive or potentially synergistic contribution. However, compatibility with other IPM components needs to be considered carefully as there is already evidence in some systems that resistance chemicals have confounding effects, for example against virus.

Agro-ecosystem resilience to pests

Issues relating to landscape ecology and ecosystem services can be discussed with regards to structure of the agricultural landscape including cropping patterns in time and space (intercropping and timing), selection of legume crop species, cultivation practices of crops, soil nutrients and water, and integration of pest control elements. Actions and interventions falling under these categories can be rated according to their impact, or potential impact, on pest management. The specific actions or interventions reported in the literature were rated according to their current level of implementation, nearness to use (if not fully developed at this stage), efficacy or potential efficacy for pest control, effect or potential effect on ecosystem services, and ease or potential ease for local implementation. The tables in each section below list the literature relating to the interventions together with ratings that have been given by the authors based on this literature. In each of the sections below, some general trends have been identified.

Crop patterns and timing

In the majority of examples found, the evidence suggests that the manipulation of spatial cropping patterns usually has relatively low impact on pests, but depending on other constraints, is potentially relatively easy to implement. This is sometimes a positive economic benefit and often positive ecosystem benefits (Bottenburg et al 1998; Braun 1997). There is much scope to increase its use. One aspect of cropping pattern change which can have a dramatic effect is the tactic of pest avoidance by altering crop timing; this was reported to have potentially high efficacy in the right circumstances (Bottenburg et al 1998).

Legume intercrops with maize or other cereals has frequently been reported to be effective in weed suppression (Ossom and Thwala 2005) Striga incidence can be reduced by intercrops (Cardwell and Lane 1995). The timing of sowing of the intercrop in relation to the 'main' crop is an important issue which deserved more investigation because its effects can be crucial (Shave et al 2012). There are a few cases where reductions in pests other than weeds or parasitic weeds have been associated with legume intercropping. Termite control can be improved (Sekamatte et al 2003) and Edemoa et al 1997 reported that fungal diseases were reduced in a cowpea intercrop but that virus diseases increased. There a fairly large number of reports of failure to show an effect on non-weed pests and in some cases evidence that pest problems were worse in intercrops. With regard to insects in general and particularly beneficial insects, Hautier et al (2002) found no effect on entomofauna diversity, Zongo et al (1993), that shootfly populations were unaffected, and Kyamanywa et al (1993), that predator fauna in the intercrop was not enhanced compared to single-crop plots. Some other issues emerge with intercrops: the importance of the choice of legume (Sekamaate et al 2003) and the degree to which yield penalties occur due to competition between crop species; often they appear to be minimal or non-existent (McIntyre et al 2001; Wortmann et al 1992). Extending the cropping pattern to include other features such as trap crops (Srnivasan et al 1994) or 'precision margins' (Waage and Schulthess 1989) appear to have had limited impact on pests and but the effect of margins on ecosystem services is generally positive, essentially creating semi-wild habitat within the crop matrix (see later section).

Intercropping can form part of what has been described as 'conservation cropping', an approach typically characterised by minimal soil disturbance, planting to achieve maximum soil cover and the use of diverse crop rotations (Siddique et al 2012). There has been quite a lot of interest in legume cover crops increase soil cover and can be incorporated into the soil as green manure. Compromises arise because sometimes the best bet suppression is achieved with legume varieties less favoured by farmers e.g. creeping varieties of cowpea (Vissoh et al 2008). Beneficial effects of cover crops on soil quality and also pest control can be timing-dependent (Agboka et al 2013). Cover crops in general have positive effects on soil fertility and quality (Barthes et al 2006) and can greatly enhance soil biota (Blanchart et al 2006). Effects on pests can be undesirable however. Amed et al (2012) found increased problems with foliar and soil-borne diseases in the conservation cropping system compared to a traditional system. Carryover of soil insect pests between crops can be worse (Medveck et al 2006). Sometimes there can be compensatory effects so that whist pest infestation may be worse, yield may be improved due to enhanced soil nutrition and moisture (Chabi-Olaye et al 2005).

Control method / Intervention	Target pest	Target Crop host	Current implemenation	Nearness to use	Effecacy /potential efficacy on Pest	Effect on ecosystem services	Local implementation	Primary Source
Intercropping	cowpea	various	moderate	current	very low	positive	easy	Bottenburg et al 1998
Intercropping	maize stem borers	various	very low	close	low	positive	moderate	Braun 1997
Trapcrop chickpea / pigeonpea	Helicoverpa armigera	various	very low	close	low	negative	easy	Srinivasan et al 1994
Pecision margins	various	various	very low	close	low	very positive	moderate	Waage & Schulthess 1989
Residual moisture, dry-season crop	Maruca vitrata	cowpea	moderate	current	high	positive	easy	Bottenburg et al 1998
Legume cover crop	Mussidia nigrivenella	cowpea	very low	close	low	positive	easy	Agboka et al 2013
Conservation cropping	Nematodes	chickpea	low	close	none	positive	moderate	Amed et al 2012
Conservation agriculture	general	legumes	very low	moderate	low	positive	moderate	Siddique et al 2012
Legume rotations	general	legumes	low	close	low	positive	moderate	Lupwayi et al 2011
Legume (cowpea) cover crop	weeds	maize	very low	close	low	positive	difficult	Vissoh et al 2008
Lablab cover residue removal	chafer grub	Phaseolus	low	close	moderate	neutral	easy	Medveck et al 2006
Legume crop cover	general	maize	low	close	none	very positive	moderate	Barthes et al 2006
Sequential oilpalm inercropping	general	legumes	none	distant	none	positive	difficult	Udosen et al 2006
Intercopping	weeds	Phaseolus	low	close	moderate	positive	moderate	Ossom & Thwala 2005
different legumes	Stemborer	maize	low	close	none	positive	difficult	Chabi-Olaye et al 2005
Relay cropping legume shrubs	Striga	sorghum	very low	moderate	low	positive	difficult	Reda et al 2005
Various Legume intercrops	Termites	maize	low	close	moderate	positive	moderate	Sekamatte et al 2003
Legume intercrops	weeviles & nematodes	banana	low	distant	none	positive	difficult	McIntyre et al 2001
Legume fallows	general	upland rice	low	close	low	very positive	moderate	Becker & Johnson 1999
Legume fallows	general	upland rice	low	close	low	very positive	moderate	Becker & Johnson 1998
Intercropped cowpea	diseases	cowpea	low	moderate	low	neutral	difficult	Edemoa et al 1997
vegetable & legume intercrops	Striga	cowpea	low	moderate	moderate	positive	difficult	Cardwell & Lane 1995
cowpeas maize mixture	legume flower trips	cowpea	low	close	low	neutral	moderate	Kyamanywa et al 1993
sorghum cowpea intercrop	shootfly	sorghum	low	distant	none	neutral	moderate	Zongo et al 1993
Banana bean intercrop	general	bean	low	distant	none	neutral	difficult	Wortmann et al 1992
Legume (Mucuna) cover crop	general	maize	low	close	none	very positive	moderate	Blanchart et al 2006
Legume fallows	general	miaze	low	close	none	positive	easy	Cheruiyot et al 2003
Fodder legume intercrops	general	sorghum	very low	close	very low	positive	moderate	Hautier et al 2002
Crop mixtures and natural enemies	general	various	very low	moderate	low	positive	difficult	Nampala et al 1999
Timing of macuna intercrop	weeds	maize	low	close	moderate	positive	moderate	Shave et al 2012

Cultivation practices of crops

With regard to cultivation practices involving legumes, most of the literature that does not concern intercropping examines legume rotations with other crops. Beneficial effects of legume rotations have been demonstrated in relation to Striga (Kabambe et al 2008; Samake et al 2006), non-parasitic weeds (Becker and Johnson 1999; Gbanguba et al 2001) and to some soil pests, notably nematodes (Haroon et al 2011; Bado et al 2011; Danga et al 2009) and termites (Sileshi and Mafongoya 2003).

Legume rotations and in particular short-duration legume fallows have a beneficial effect on soil structure and fertility (Becker and Johnson 1998, 1999; Cheruiyot et al 2003; Kilya et al 2010; Barthes et al 2004) and a positive effect on biological processes in the soil (Lupwayi et al 2011). These changes can translate into improvements in yield (Thierfelder and Wall 2010) but it is likely that yield improvements achieved in the controlled conditions of field trails are somewhat less common in farmer's plots (Hikwa and Waddington 1999).

The beneficial effect of legume rotations can be contingent on a variety of factors, with effects most noticeable when soil conditions were more favourable (Becker and Johnson 1998). The species of legume selected is important, with for example groundnut but not cowpea having some effect against nematodes in a rotation with sorghum (Bado et al 2001). A mixture of cassava and cowpea gave the highest yield and fewest weeds in a rotation with rice (Gbanguba et al 2011). Issues of legume species effect on agro-ecosystem services must also be set against a background of farmer preferences for certain types. Other legume characteristics are important the acceptance of novel cultural practices incorporating legumes (Snapp and Silim 2002). It may be necessary to maintain the rotation cultivation practice for a number of years before effects become evident, with Striga suppression for example (Kabambe et al 2008) and the benefit may be quickly lost when the rotation practice ceases (Samake et al 2006). The evidence is clear that rotation practices involving legumes and legume fallows can significantly improve agroecosystem resilience making the system more robust in the face of pest damage rather than having a great direct effect on most pests. More can be done to facilitate farmers to explore novel tactics for the use of a variety of legumes in their existing cropping systems.

Control method / Intervention	Target pest	Target Crop host	Current implemenation	Nearness to use	Effecacy /potential efficacy on Pest	Effect on ecosystem services	Local implementation	Primary Source
Legume rotations	general	legumes	low	close	low	positive	moderate	Lupwayi et al 2011
Legume fallows	general	upland rice	low	close	low	very positive	moderate	Becker & Johnson 1999
Legume fallows	general	upland rice	low	close	low	very positive	moderate	Becker & Johnson 1998
Legume fallows	general	miaze	low	close	none	positive	easy	Cheruiyot et al 2003
Legume mulch prior to next cop	root knot nematode	tomatoe	none	moderate	high	positive	moderate	Haroon et al 2011
Legume rotations	Nematodes	sorghum	low	moderate	moderate	positive	moderate	Bado et al 2011
Conservation agriculture green manure	general	maize	low	close	very low	very positive	moderate	Thierfelder & Wall 2010
Legume rotations	nematode & disease	wheat	low	close	moderate	positive	moderate	Danga et al 2009
legume rotations	Striga	maize	low	moderate	moderate	positive	difficult	Kabambe et al 2008
legume matter as fertilizer	various	maize	very low	moderate	very low	positive	difficult	Chikowo et al 2007
Cowpea fallow	Striga	millet	very low	moderate	moderate	positive	difficult	Samake et al 2006
IPM technologies	various	groundnut	low	moderate	moderate	neutral	difficult	Mugisha et al 2004
Legumes types for farmers preferences	various	various	low	moderate	low	positive	difficult	Snapp & Silim 2002
Legume cover fallows	weeds	rice	low	moderate	moderate	positive	difficult	Becker and Johnson 1999
Legum (Macuna) cover	various	maize	very low	moderate	none	positive	moderate	Barthes et al 2004
Rotational legume fallows	soil insects	maize	low	moderate	low	positive	moderate	Sileshi and Mafongoya 2003
annual legumes	various	various	high	current	none	positive	easy	Hikwa & Waddington 1999
rotation with cassava soya/cowp intercrop	weeds	rice	very low	moderate	moderate	neutral	difficult	Gbanguba et al 2011
Legume green manure	weeds	potato	very low	close	low	positive	moderate	Kiiya et al 2010

Combination of pest control elements

A good number of reports of various combinations of pest control measures report high efficacy. Most of these involve chemical control or varietal resistance combined with cultural practices. All present varying degrees of difficulty in local implementation often because of access to and the correct use of the inputs or equipment.

A number of papers report high pest control efficacy in the field by using various combinations of insecticide with some form of cultural control of host-plant resistance. Timing of pesticide applications with the aim of having most effect with fewest applications is an important theme (Karungi et al 2000; Kamara et al 2007; Marko 2000). Ekiyar et al 2003 was able to demonstrate that a regime of reduced sprays delivered higher returns than traditional practices in the cultivation of groundnut and cowpea. A particular combination of close plant spacing, early planting and a recued number of carefully-timed sprays was reported to be favoured in farmer participatory trails of cowpea (Nabirye et al 2003).

The evaluation of combined measures is sometimes difficult because it is not always possible to disentangle the effects of the different components. Judging by the modest effects usually obtained with most cultural measures, it is likely that the high pest control efficacy is usually achieved by host-plant resistance, by synthetic pesticides, or both. Where particularly a conventional insecticide is used as one of the components the effects on ecosystem services and agro ecosystem resilience are likely to be impaired.

Control method / Intervention	Target pest	Target Crop host	Current implemenation	Nearness to use	Effecacy /potential efficacy on Pest	Effect on ecosystem services	Local implementation	Primary Source
Insecticides + intercroping + sowing date	various	cowpea	low	current	high	negative	difficult	Nabirye et al 2003
Insecticide timimg + sowing date	various	cowpea	low	current	high	negative	difficult	Karungi et al 2000
Spray schedules	various	cowpea	low	current	high	negative	difficult	Kamara et al 2007
lambdacyhalothrin timing	various	chickpea	low	current	high	negative	difficult	Marko 2000
Insecticide + host-plant resistance	virus vectors	cowpea	low	current	high	negative	difficult	Ambang et al 2009
Insecticide + sowing date + hp resistance	various	cowpea	low	current	high	negative	difficult	Javaid et al 2005
Insecticde + pheronome + bird perches	Helicoverpa armigera	chickpea	low	current	high	negative	difficult	Singh et al 2009
Insecticide multiple application	various	Phasoelus	low	current	high	negative	difficult	Karel and Ashimogo 1991
close-spacing+early pl+red.timed spr.	various	cowpea	low	close	high	negative	moderate	Nabirye et al 2003
IPM packages with reduced sprays	various	gn + cp	moderate	current	high	negative	moderate	Ekiyar et al 2003

Selection of legume species

A fairly large number of legume species have considerable agricultural potential, are very under-utilised, and offer a positive effect on ecosystem services through increased diversity. Their impact on pest infestation is also likely also to be positive because increased crop diversity spreads risk when pest attack occurs.

Crop	Current level of utilisation	Its use increases food security	Improves nutritional balance	Cash-earning potential	Suitability in agro-ecosystem	Ease of local uptake	Effect on ecosystem services	Potential level of utilisation
Cowpea	high	considerably	considerably	high	high	high	positive	very high
Groundnut	very high	moderately	considerably	high	high	high	positive	very high
Soybean	high	moderately	considerably	high	high	high	positive	very high
Phaseolus vulgaris	very low	moderately	very considerably	moderate	high	high	positive	moderate
pigeonpea	moderate	moderately	considerably	moderate	high	high	positive	high
bambara beam	low	considerably	considerably	moderate	very high	high	very positive	moderate
peas	moderate	considerably	considerably	moderate	very high	high	very positive	moderate
'minor legumes'	very low	considerably	considerably	low	very high	moderate	very positive	high
lablab bean	very low	moderately	moderately	low	high	moderate	very positive	moderate
yambean	very low	moderately	considerably	low	high	moderate	very positive	moderate
locust bean	very low	moderately	considerably	low	high	moderate	very positive	moderate
yardlong bean	very low	moderately	considerably	low	high	moderate	very positive	moderate
marama	very low	moderately	considerably	low	high	moderate	very positive	moderate
greengram	very low	moderately	considerably	moderate	high	moderate	very positive	moderate
blackgram	very low	moderately	considerably	low	high	moderate	very positive	moderate
Lathrus sativas grasspea	very low	considerably	moderately	moderate	high	low	positive	moderate
chickpea	moderate	considerably	considerably	high	high	high	positive	high

General ecology and structure of agroecosystems

A number of papers relating to agro ecosystem resilience in cropping systems other than legumes offer a largely theoretical discussion of the elements of agro-ecosystems required to deliver sustainable complete agro-ecosystem solutions. It is probably very difficult to effectively implement all the elements successfully. There are a number of papers that discuss enhancement of landscape structure and with an associated increase in biodiversity, most of which are theoretical but few report evidence. All postulate or report a positive or very positive effect on ecosystem services, but there is little focus on, or evidence presented, of improved pest management. To achieve the nature of the changes discussed on the scale required is at best difficult, current implementation is patchy and small scale.

There has been more focus on agro-ecosystem scale thinking in Asian rice systems than in other crops or continents and Savary et al 2012 attempted to distil some key principles which they argue underpin sustainable pest management in rice. These are: system diversity, host plant resistance, facilitating hierarchies in biological and social systems, and a supportive political context. These principles find expression in many of the other papers in this section and in a minority of cases actual practical examples rather than simply rhetoric.

The idea of diversity is discussed in terms of numbers of species and indeed what constitutes a good number of species to provide functional biodiversity (Gangatheran and Neri 2012), and in terms of biotic network structures and the form they need to take to achieve the desired ends. (MacFayden et al 2011). Landscape heterogeneity is also a much-heralded tenant of ecosystem resilience, and a number of issues have been considered. Farm-level heterogeneity is proposed and discussed as a means of increasing system robustness (Arce-Nazario 2011). The inclusion of natural habitat in this mix is also generally believed to be a key feature of the approach. Lovell and Johnston (2009) suggest that a matrix incorporating small patches of semi-natural habitat may be beneficial. Such patches of wild habitat have been shown to have positive effects of ecosystem services, specifically pollinators (Gemmill-Herren and Ochieng 2008). Lonsdorf et al (2009) attempt to identify factors which predict value for ecosystems services and develop predictive models with mixed success.

Another theme which is apparent is the scale on which agro ecosystem management is required and most authors on the subject think that wide-scale approaches are necessary, both to achieve general agro-ecosystem resilience (Cumming and Speisman 2006) and more specifically in order to advance approaches to IPM beyond its present limits (Birch et al 2011). Linked to scale is the idea that approaches need to be more holistic rather the piece-meal (New 2005).

Some warnings are offered, however, highlighting the complex trade-offs that exist in providing ecosystem services encompassing a wide range of goals (Cheatham et al 2009) and the complex range of ecosystem features which support those services, e.g. pollinators (Potts et al 2001). Finally in thinking about enhancing diversity with exotic legumes, of which there is some evidence of this happening in Africa, it may be well to remember the Australian experience where a number of 'useful' legumes have become serious rangeland weeds (Paynter et al 2003).

Control method / Intervention	Target pest	Target Crop host	Current implemenation	Nearness to use	Effecacy /potential efficacy on Pest	Effect on ecosystem services	Local implementation	Primary Source
Diveristy+HPR+Hierarchies+Policy	various	rice	none	distant	moderate	positive	very difficult	Savary et al 2012
Restore functional Biodiversity	various	various	none	distant	low	positive	difficult	Gangatheran and Neri 2012
General advances in IPM	various	various	none	distant	moderate	positive	very difficult	Birch et al 2011
Biolgical community networks	various	various	none	very distant	low	positive	very difficult	MacFayden et al 2011
Hetergeniuos habitats	various	various	low	moderate	moderate	positive	moderate	Arce-Nazario 2011
Enhancing ecosystem services	various	pathogens	none	distant	low	positive	very difficult	Cheatham et al 2009
Landscape structure	none (enhance pollinators)	various	low	moderate	none	very positive	difficult	Lonsdorf et al 2009
Natural Landscape elements	various	various	low	distant	none	very positive	difficult	Lovell and Johnston 2009
Natural Landscape elements	none (enhance pollinators)	Egg-plant	low	moderate	none	very positive	difficult	Gemmill-Herren and Ochieng 2008
Regional scale ecosystem	various	various	none	very distant	low	very positive	very difficult	Cumming and Speisman 2006
Invertebrate conservation methods	various	various	low	moderate	moderate	very positive	difficult	New 2005
Wide-scale ecosystem structure	none (enhance pollinators)	various	low	distant	none	very positive	very difficult	Potts et al 2001
New legume species imports	various	various	very low	moderate	none	very negative	moderate	Paynter et al 2003

Potentially productive avenues for future work relating to pest management in the context of agroecosystem resilience

The aspects of cropping system diversity discussed above would appear to be a worthy goal not because they deliver particularly effective pest management, because they do not, but because they buffer the agro-ecosystem against such attack by spreading risk, increasing plant health, increasing plant pollination, enhancing beneficial insects, improving soil fertility and soil moisture. These are all more subtle and less immediate gains than dead insects and a clean crop, so the challenge is through participatory approaches to facilitate movement towards, and experimentation with, these practices which offer greater agro ecosystem resilience. Many authors discuss the need for more wide-scale agro-ecosystem change but it is important to remember that particularly in systems with many small farms, all change is always local because the individual farmers must make the decisions. A wider-scale is provided by the political environment which can help or hinder local change. The literature is clear that legumes currently play a crucial role in agro ecosystem resilience and it would appear to be a role that can be adapted and increased by participatory experimentation to establish tactics for legume integration in cropping systems which suit local conditions.

Participatory development of IPM for small-holder farmers in Africa

What is the experience of participatory IPM in Africa?

Farmer field schools are considered one of the most appropriate mechanisms for building farmer capacity for agroecological crop management, as they focus on the "how and the why" of crop/pest performance rather than promoting prescriptive technologies. FFS are a means to build farmer capacity for managing healthy crops, and it involves processes of agroecosystem analysis, discovery learning and group experimentation (Duveskog 2006). Agroecological crop management by its nature requires a process of adaptation to the ecological conditions of the farms and the social and economic practices and capacities of the farming family. This process requires an understanding by the farmer of the "how and why" of crop-pest interactions in order to adapt the knowledge and management practices to their local conditions. At the most fundamental level this education process empowers farmers; a social study in Kakamega, Kenya found that FFS enabled farmers to understand that crop failures are not due to witchcraft, but due to poor crop management (Fris-Hansen et al 2010). This realization reduced social conflicts and empowered farmers to address the problem. Furthermore, FFS provide a forum for exchange of knowledge between farmers and with extension or research staff; in some cases secondary level associations have been formed between FFS to provide better knowledge management services and engagement with research institutes and agricultural services (Karanja-Lumumba et al 2007).

There has been substantial use of farmer field schools to develop pest management capacity among farmers in SE Asia (Van Huis & Meerman 1997) where it has particularly focussed on reducing pesticide use. While the FFS in Africa often started as IPM or Integrated Pest and Production Management (Braun et al 2006), overall for FFS schools in Africa the main themes appear to have been improved soil fertility management, livestock health, and general organization and empowerment of farmers to access services. Although there are cases of pest management focused groups (e.g. Nathaniels, 2005, Gill 2004), pest management appears less prevalent than in FFS in SE Asia (Orr 2003). FFS are credited with having substantial impacts on productivity and income including for more marginal farming groups as well as better off ones (Davis et al 2012), but the impacts reported appear to be more from empowerment and improved soil fertility management than IPM. Some authors have indicated that pest control was not a priority for farmers, and as few pesticides were generally used their reduction has not been seen as priority (Braun et al 2006, Orr 2003). Nevertheless, FFS have or are being used as a means to massively scale-out up-take of simple technologies for agricultural improvement (e.g. KARI in Kenya) as they can be largely managed by experienced farmers through farmer to farmer exchanges (Braun et al 2006).

What is farmer acceptance and use of different IPM and participatory approaches?

A first consideration is what types of IPM practices are appropriate for the farmers involved. Orr 2003 indicates that for IPM of non-cash crops farmers need host plant resistance, biological control – technologies that don't require investment by farmers; or IPM technology has to contribute to overall system productivity e.g. soil fertility. There is a need to recognize the time investment required to learn and implement ecological pest management through FFS approaches of understanding pest life-cycles and scoring of pest incidence. Knowledge based ecological management through discovery exercises etc. should be focussed on those problems where they have the potential to generate real savings in pest management. Such investments should only be promoted where there is a real prospect of it generating savings in the implementation of pest management (i.e. reduced use of pesticide) or reduced likelihood of crop losses (increased food security). This often needs to be complemented or be replaced by trials of alternative pest control or crop management practices, which farmers can more readily evaluate as to their effectiveness under the farmers cropping system.

However, also it also needs to be considered whether the depth of understanding required e.g. pest life-cycles etc. was felt to be too complex to address in FFS. As noted by Van den Berg 2007 "Complex pest management information, however, does not readily diffuse among farmers but has to be acquired through experiential learning." Erbaugh et al 2010 contend that initial knowledge focussed IPM had limited impacts, in a change to technology transfer of an IPM package for pest control in cowpea led to increased uptake of IPM practices by farmers, but then individual farmers adopted different elements of the package adapting it to their own needs. Orr 2003 indicates the time required by farmers to learn and implement knowledge intensive IPM techniques such as scoring pest incidence is often more than farmers are willing or able to invest relative to the importance of the loss from the pests. Overall the investment in IPM is only worthwhile when crop losses are high and/or the crop has a high economic value. However, not only do the farmers have to acquire this understanding so do the agricultural "extension" agents managing the FFS. Erbaugh et al (2007) identify the lack of IPM knowledge of extension agents in Uganda as a significant impediment IPM implementation to farmers.

FFS are an education and agricultural development approach and not a research technique. Research is required to develop and validate the learning techniques (agroecosystem analysis methods, discovery learning exercises and group experimental processes) that will enable farmers to understand the crop-pest relations in their crops and how to more effectively manage them, but this investment may not be appropriate for all farmers and all crop pest problems. The interface between FFS and research is the development of the curricula content for particular crop/pest or other interactions. Research is needed to adequately understand the crop-pest relationships and their response to different environments etc. to develop these curricula. Participatory research with farmers is required to develop and validate the discovery learning processes that will enable farmers to reach robust conclusions about the management of their pests and crops.

How can research on IPM appropriately engage farmers?

If Orr 2003 analysis is accepted then FFS-type discovery-learning approaches to developing IPM capacity are not a viable investment for farmers managing pest problems in subsistence food crops. In these cases host plant resistance is the most appropriate technology, or other low-cost approaches to biological control. Such approaches still need validation with farmers to ensure that new planting materials are acceptable to farmers meeting the broader set of characteristics that farmers require (e.g. Haggar et al 2001). Farmer participatory research processes would firstly ensure materials being developed are acceptable and subsequently farmer experimental approaches such as the Local Committees for Agricultural Research (CIALs) or farmer to farmer interchanges allow farmers to test and disseminate new varieties or practices.

In those cases where control of the pest requires greater investment, whether learning about pest biology and monitoring for effective use of control technique or manipulation of the agroecological environment (e.g. companion planting etc.), it is probable these will only be implemented where the crop has some economic value (Orr 2003). The application of such techniques will likely require an educational process such as FFS. While it is not the role of a research programme to implement such educational processes, it is the role of research to develop and validate the methods to be taught in such processes. As indicated above, this has two elements: firstly validation with farmers of the agroecological management approaches, and secondly, the development of the educational curricula that enable farmers to understand and adapt these approaches. This requires that the research processes are implemented in participation with interested and representative farmer groups; although typically not the poorest farmers, as they cannot afford to make investments in such processes that may not bring them immediate benefit. Subsequently a strategy is required for dissemination of the methods developed to "extension" services with capacity to implement such techniques with larger numbers of farmers.

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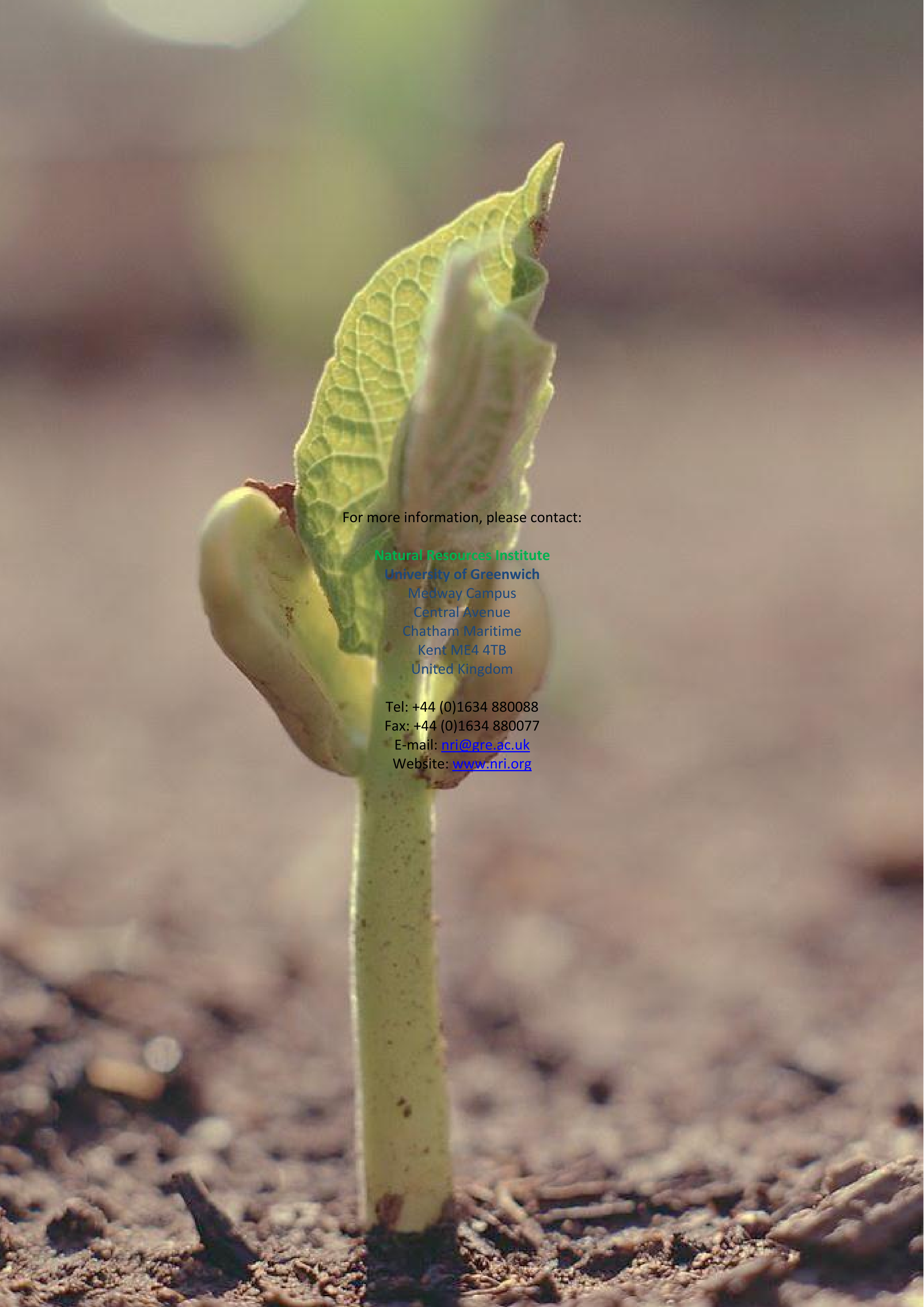

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