Sustainable plant protection for increased food security in a changing climate

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Challenges to food security in a changing climate

The global climate is changing. Rising temperatures in temperate regions are making headlines, but there are a host of changes that may have even greater impact on a global scale, particularly in regions where food security is already delicately balanced. Rising sea levels, changing patterns of rainfall, availability of water and increasing concentration of carbon dioxide in the atmosphere are all likely to affect the biotic environment upon which we depend.

Biologists working with insect pests and diseases in the agricultural landscape are familiar with the idea that interactions between organisms are sensitive to both abiotic factors such as climate and biotic factors such as plant physiology. Changing climate will lead to the emergence of insect pests in areas in which they have previously been absent, but may also alter relationships between pests and their host plants, and the implications may be difficult to predict. Since many of the world's subsistence farming systems are continuously threatened by insect pests and diseases, they must be robust in order to survive.

The world is also influenced by the economic climate. In recent years, demand has led to rising food and fuel prices, putting increased strain on the household economies of millions of people. This trend looks set to continue, at least in the medium term, and will amplify the threat posed by changing weather alone. There is a general belief that human activities contribute to the major aspects of changing weather, and the world's economy is driven by a multitude of complex of factors. As biologists however, even if we need not enter the debate on the driving forces, the message is clear: climate change is happening, it will likely pose huge challenges to global food security and we must find ways to adapt and deal with it.

Subsistence farmers are generally adept at producing food under difficult circumstances using skill and knowledge adapted to local conditions, but the challenges posed by changing meteorological and economic climates will greatly test their adaptability, and the robustness of their cropping systems. For these farmers, access to sustainable cropping that minimizes losses to insect pests but does not require inputs of broad spectrum synthetic insecticides pesticides will become even more vital.

Role of sustainable crop protection for food security

Insecticides and global agriculture have enjoyed a generally successful and productive relationship. In subsistence farming systems there are certainly many examples where correctly applied insecticides have been vital in ensuring food security for individuals and communities. However, subsistence farming is often characterized by limited access to insecticides, or incorrect use leading to health and environmental problems. Regions that are not currently dependent upon subsistence farming may also come into focus. Changing climate may expose these crop systems to new pests and diseases, while increasing demand for insecure supplies of energy and harvested products may encourage a return to food production on a smaller, local scale. At the same time, political prudence and public opinion will probably continue to call for dramatic reductions in pesticide inputs to the landscape, minimising growers' options for chemical plant protection. These factors may make sustainable plant protection against insect pests a much wider global issue in the years ahead.

Chemical ecology is the study of how organisms interact with each other and the environment via chemical cues or signals. Many major developments in the field have related to the discovery of insect pheromone communication systems, some of which have been successfully exploited in crop protection. This approach however is not always suitable for subsistence cropping systems. Chemical ecology is now focusing increasingly on the understanding of plant-insect and plant-plant interaction. Insects that are crop pests are generally herbivorous, and have developed sophisticated systems for finding and assessing suitable host plants and avoiding unsuitable ones. They achieve this to a great extent by the detection of plant chemicals. Predators and parasites of the pests may also be tuned into the same chemical signals, using them as a short cut to find their prey.

By unravelling the complex web of chemical communication, biologists can exploit these chemical interactions and manipulate the behaviour of pests and their natural enemies. Integrated pest management (IPM) traditionally employs a range of measures, sometimes including intervention with pesticides. However, the use of simple and cheap solutions based on suitable plant species is a far more suitable approach for protecting food security in small-scale subsistence production. Knowledge on plant-insect interactions and chemical ecology allows scientists to combine plant species in cropping systems founded on increased plant genetic diversity. This can often provide more stable and thus sustainable suppression of pest insects.

In this article we highlight how this research-based approach can be implemented, focussing on subsistence farming systems in different parts of the world- production of maize and sorghum in east Africa and vegetable production in Sri Lanka. In the former system, insecticides are not an option for farmers, while in the latter they create problems for public health and the environment. Farmers in both systems live under challenging economic and environmental circumstances in which the threat posed by insect pests is high and food security is of prime concern. Both systems would benefit greatly from implementation of new sustainable approaches to plant protection against insect pests.

Sustainable crop protection for food security in Africa

Lepidopterous stemborers are the most important pest for maize throughout Africa. The main method recommended for control involved the use of insecticides. However, resource-poor, small-scale maize farmers in Eastern and Southern Africa are unable to afford their use, and, furthermore, they constitute a potential hazard to the local environment, and also to human and animal health. Thus, until the mid-1990s, there appeared to be no available option for farmers to control such pests, with year upon year substantial losses in yield upon harvest. At this stage, scientists at the International Centre for Insect Physiology and Ecology (*icepe*) in Kenya, in collaboration with the Chemical Ecology Group at Rothamsted, embarked upon a programme of research aimed at exploiting local Kenyan biodiversity in the search for naturally attractive and repellent plants that could be deployed, as a 'push-pull' system, alongside maize crops, for stemborer control.

This system, also known as the 'stimulo-deterrent diversionary strategy (SDDS)', was devised in the early 1990s as a means for deploying volatile semiochemicals in a sustainable manner for insect pest control. Here, insects are pushed away from the crop to be

Tea cultivation in the Sri Lankan upcountry, showing plots where tea workers grow vegetables.

protected by repellent intercrops, and are simultaneously lured to attractive trap crops. For the stemborer problem, studies were initially aimed at surveying wild plant species as potential hosts. In replicated small-plot experiments, Napier and Sudan grasses had high levels of oviposition, whereas molasses grass had hardly any infestation. Legumes are not attacked by stemborers, and it was shown that silverleaf and greenleaf were repellent. When using either Napier or Sudan grass as a perimeter trap crop surrounding maize, higher numbers of moths were found on the trap crops. When using molasses grass between rows of maize, the number of stem-borers was significantly reduced. Furthermore, an additional bonus was the enhanced attraction of stemborer parasitoids when molasses grass was used. When either intercrop was used in conjunction with the trap crop, the largest reduction in stemborer numbers on maize was observed.

The next stage was to provide the underpinning science for the trap crop and intercrop effects. Using gas chromatography coupled to insect electroantennography (GC-EAG), the key olfactory cues used by stemborers in host location were located by analyzing the volatiles collected from maize and Napier grass, identified using coupled GC-mass spectrometry (GC-MS). These included octanal, nonanal, naphthalene, 4-allylanisole, eugenol and linalool. The key cues used in avoidance of molasses grass and silverleaf were also identified, and included ocimene, terpinolene, caryophyllene, humulene and 4,8-dimethyl-1,3,7-nonatriene, for molasses grass, and Ocimene, nonatriene and other sesquiterpenes for silverleaf. The identification of these compounds was an important measure in case of possible future breakdown in the 'push-pull' system, whereby the identified semiochemicals could be used as quality control markers.

Back in the field, wider studies on the 'push-pull' system of maize, trap crop and intercrop showed increased yields in maize, compared to control plots of maize, maize + trap crop, and maize + intercrop. The benefit of increased yields in maize was demonstrated by subsistence farmers working in conjunction with *icipe* scientists, and the 'push-pull' system was eagerly taken up by farmers. Benefits of the system, in addition to increased food security, are income generation by sale of maize, cattle fodder and silverleaf seed, and increased livestock milk and meat production. Further benefits include improved soil conservation and fertility, and enhancing biodiversity. In a social context, the improvement in the agronomic situation protects fragile environments through reducing pressure for human migration, and improved quality of life for youth groups in rural areas, reducing migration to urban areas. Thus, increased food security along with a range of tangible economic and social benefits for subsistence farmers quickly arose from providing an agricultural solution, based on scientific understanding of plant-insect interaction and its underlying mechanisms.

Sustainable crop protection to reduce pesticide dependence in Sri Lanka

Sri Lanka's major export crop, tea occupies 165,000 ha or 2.5 % of its area, provides employment to over 300,000 workers and earns 15% of its export income. Vegetable farming provides an avenue for tea workers of the upcountry to supplement their meagre income by either farming their own small plots or obtaining casual employment in larger vegetable farms established in valleys in tea areas. Contamination of tea by seepage of pesticides used in the vegetable plots and farms in tea areas was perceived as a risk to the 'clean' (low pesticide) nature of Sri Lankan tea and any such evidence would threaten continued vegetable farming in tea lands with consequent effects on worker income. A study supported by Sida-VR was carried out on pesticide usage among vegetable farmers in tea lands, and pesticide residue levels in tea lands were studied in order to assess the threat to workers' health and to tea cultivation.

In a survey of 127 vegetable farmers in upcountry tea lands growing mainly carrot, leek, beans, beet and cabbage, over 97% of whose plots were within 500 metres of tea lands or streams providing water to dwellers in the neighbourhood, it was found that 98% used insecticides, 88% fungicides and 15% herbicides in their plots. Among the insecticides, organophosphates, mainly chlorpyrifos and to a lesser extent dimethoate, profenofos, diazinon and phenthoate were popular with the farmers. Cyromazine, a triaminotriazine and permethrin, a pyrethroid, were also used by a few farmers. Most of the farmers were found to disregard guidelines given on the label of the pesticide. Irrespective of the pest and the type of insecticide or fungicide used, more than half the farmers maintained a pesticide-application interval of 7-8 days while a third used intervals of 14-15 days. When preparing spray mixtures, the number of cups of pesticide per sprayer-tank of water remained the same irrespective of the type of pesticide and the sizes of cups and sprayer tanks. During rainy seasons, farmers would apply pesticide mixtures of higher concentration with increased frequency. When preparing spray mixtures, the number of cups of pesticide per sprayer-tank of water remained the same irrespective of the type of pesticide and the sizes of cups and sprayer tanks. During rainy seasons, farmers would apply pesticide mixtures of higher concentration with increased frequency.

During the application of pesticides, the majority of farmers wore regular clothing without protective wear such as gloves, mask, shoes and hats. The choice of pesticides was based on recommendations from fellow farmers and to a lesser extent from salesmen and local stockists of pesticides. Some based their decision on experience from previous work. Only two farmers were influenced by television advertisements while none mentioned radio or newspaper as a source of information. All farmers expected a reduction in yield if pesticides were not used with estimates of loss ranging from 90-100% (8 farmers), 75-85% (29), 50-70% (53) and 20-40% (34).

A study was also undertaken on the effects of pesticide use in large scale vegetable fields on neighbouring tea fields and their environment. It was found that residue levels of pesticides in made tea from fields 1.5-3 metres away from vegetable plots was not at present a threat to the tea industry and that the persistence of these pesticides on tea flush was for periods expected for them on plant surfaces. Pesticide residues in soils were also in agreement with the behaviour expected for the sandy loam soils where tea grows.

Residue levels in the leaves of a typical vegetable, cabbage nine days after spraying were about 10% higher than their specified limits. Our work suggests that pesticides were being applied at high doses and that the guidelines regarding pre-harvest intervals were not being followed. Residues in water of Chlorpyrifos-ethyl (up to 0.006 ppm) and diazinon (up to 1 ppb) were found to be above the EU specified limits for these pesticides in drinking water (0.1 ppb), suggesting that the use of chlorpyrifos-ethyl and diazinon in vegetable cultivation posed a threat to health and the environment as many households in the region relied on the stream water for their daily needs.

Thus it was clear that the environment and the health of the inhabitants could benefit from alternative approaches to insect pest management. In a Sida-VR funded collaboration between the Horticultural Crop Research and Development Institute (HORDI), University of Peradeniya and SLU Uppsala, we showed that it was possible to protect crops against a major insect pest by exploiting chemical interactions in intercropping. In a strategy designed to reduce losses of beans (*Phaseolus vulgaris*) due to the stem mining bean fly (*Ophiomyia phaseoli*), we grew leeks within bean plots. In laboratory experiments with a range of possible intercrops, leek odour was found to repel flies and prevent fly orientation to the odour of the bean host plant. Mixed cropping of beans with leek in alternate rows significantly reduced adult bean fly settling and emergence, and losses of bean plants compared with a mono crop.

When grown with leek, bean yield per row was significantly higher than that of mono cropped beans, reflecting the protective effect of leeks. An economic analysis of the potential benefits of the bean-leek system showed that, although the income from the sale of beans alone was reduced in mixed cropping plots, the overall income was almost four to five times greater than from mono cropping, due to the higher yield of leeks. Although the results suggest that it may be economically advantageous for the farmer to grow leeks as a mono crop rather than the mixed crop, demand for leeks is limited as they are considered a high value niche product. Thus the intercropping system would allow the farmer to gain an extra profit from this crop while simultaneously allowing more secure production of beans, an important component of the diet. The combination of plants is therefore economically viable as both crops give good monetary returns to the user, fulfilling an important requirement for the success of this kind of approach. Importantly, protecting beans in this way may reduce the farmers' reliance on insecticides, which will be beneficial not only for the environment but also for their health and economy.

Although more research would be needed before this system could be implemented in practice, it demonstrates the possibility of achieving sustainable pest management in environments in which a reliance on insecticides has developed. However, a key element would be to persuade farmers to test and adopt this new approach. Only if this can be achieved will there be a realistic prospect of breaking this dependence.

Success with farmer adoption of sustainable strategies in Africa

A major factor in the adoption of the push-pull technology in Eastern and Southern Africa was ensuring that farmers have access to knowledge of the biology and ecology of stemborers, in particular their identification, and the existence of alternative plants/grasses on which stemborers feed. This includes the organization of so-called 'farmers days", where farmers are invited to attend and observe model farms where the 'push-pull' system is in place, and description of the system through radio programmes. Such information is pivotal in the development and introduction of sustainable pest management strategies, and is not only applicable in Africa, but also for other resource-poor parts of the world where similar systems have the potential to be adopted. In Africa, the system has been widely taken up by subsistence farmers, not only in Kenya, but now also in Tanzania, Uganda, Ethiopia and Malawi, with over 1000 farms thought to have adopted the technology. This is a truly remarkable story, given that research into developing the system only began in the mid-1990s.

New roles for allelopathy in sustainable crop protection

In his classic definition, Elroy Rice described allelopathy as 'the positive or negative effect of one plant on another through chemicals that escape into the environment'. His inclusion of the term 'positive' reflects Rice's view that allelopathy could be a key resource in the development of sustainable agriculture. Allelopathy research has often focused on the negative developmental and agronomic effects of chemical transfer between plants, but recently there has been a revival of interest in allelopathy as an ecological phenomenon. This has led to opportunities for sustainable crop protection based on new discoveries on how plants interact with each other via chemical signals.

During the successful development of the 'push-pull' system for stemborer control in Africa, an unexpected discovery was encountered which has had major implications for the control of witchweed, the notorious parasitic plant pest that affects maize crops. When investigating the impact of silverleaf as an intercrop for repelling stemborers, it was discovered that there was also almost complete reduction in witchweed appearance. Subsequent collaborative studies between *icipe* and Rothamsted defined the impact of silverleaf as allelopathic, with a number of isoflavonones identified from root exudates. Current studies at Rothamsted are investigating the active principle from silverleaf that is involved in suppression of witchweed development. Thus, the 'push-pull' system has been shown to provide a low-input approach for controlling both notorious insect and weed pests of maize, with a key role for understanding of allelopathic interactions

At SLU in Uppsala, we are studying how plant chemical signalling between undamaged plants affects not only the receiving plant, but also the insect pests that feed on them along with their natural enemies. We have found that barley plants exposed to allelopathic volatiles and root exudates from aggressive weeds become less attractive to aphids, serious pests of crops in many regions, and more attractive to their natural enemies. This is the first time that the wider effects of allelopathy in an ecosystem have been studied, and the results suggest these interactions can be exploited for sustainable aphid management. We have also discovered that barley plants exposed to volatile chemical signals from barley of a different genotype reallocate biomass from roots to shoots, a possible adaptive response to dealing with the presence of a competing plant neighbour. The responding barley plants also became less acceptable to aphids but more attractive to the aphids' natural enemies.

In a Mistra-funded research program, PlantComMistra, we are aiming to exploit these chemical interactions by identifying the active inducing signals and deploying them as formulations that stimulate plant health, and through mixed barley cultivar cropping. Early field results suggest combining certain barley genotypes can reduce aphid populations. An approach based on mixed cultivars that negates the need for insecticide inputs would provide a more stable and sustainable strategy for aphid management, working in harmony with the agronomic landscape. Our approach also serves as a model for the use of allelopathy in sustainable pest management in both commercial and small scale farming.

Sustainable crop protection: an important contribution to food security in changing climates

The world's climate is changing and we need to change with it. New ideas and strategies will be required to meet the challenges faced in many parts of the world, and simple, robust approaches for sustainable crop protection will be important in supporting communities through these challenging times. It is possible that, when attempting to predict the impact of climate change on food production, policy makers may have overlooked the potential impact of the emergence of new pests and diseases. Human activities, such as increasing exchange of food and plant materials between countries and continents, will increase the risk for introduction of new pests and diseases. There are already well-documented cases from several regions of the world, and scientific research will play a vital role in our adaptation to these new scenarios.

Although there are no magic bullets, understanding of plant-insect interaction and its underlying chemical ecology can make a major contribution to the development of sustainable crop protection and the maintenance of food security. Recent work, particularly the deployment of push-pull strategies in Africa, have reaffirmed the belief that the most relevant approach for subsistence farming will be based on simple systems making use of naturally occurring plant biodiversity that not only increase yields but provide real economic and social benefits for the farming community. Pest suppression that is cheap and biologically stable, that has a low risk of imposing selection for insect resistance, and that fits with the cultural and farming practices of a particular community will be the gold standard for sustainable crop protection.

High quality science and convincing field data are not enough to ensure these strategies become practice; the farming community itself must be convinced of the benefits. The importance of this cannot be underestimated, and the East Africa work reported here exemplifies the type of approach and level of commitment that will often be required to ensure user adoption, irrespective of the region and type of farming system. As such it serves as a model that should be applicable in small-scale farming in many regions of the world and in different combinations of crops and insect pests.

In some parts of the world, insecticides are seen as a major tool for protecting food security and are used extensively by farmers, sometimes leading to health and environmental concerns. The Sri Lankan work shows that, even under such circumstances, it is possible to use an understanding of plant-insect interactions to offer farmers alternatives to pesticides. Here the major challenge will be to break the dependence on chemical spraying, highlighting the vital role of stimulating farmer adoption. The Swedish work with chemical interactions and mixed genotype cropping in barley meanwhile shows how this field of research can provide solutions for large-scale agriculture, in regions of the world where there is likely to be increased pressure to minimize pesticide inputs.

Economic forces and demand for energy and products are causing us to take an increasingly global perspective on food production, which will probably happen increasingly on a local scale. The issue of food security will take on even greater importance in developing regions, and may also become relevant in developed nations. Fundamental and applied biological research will be needed because it can provide sustainable plant protection, leading to stable, increased yields. In turn this will make food supply more reliable and less dependent on chemical insecticides. Although the times ahead will present many challenges, there are exciting opportunities to further our knowledge on the behaviour of plants and the insects that feed on them, knowledge that will help us meet these challenges. ■

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