Exploiting chemical ecology and species diversity: stem borer and striga control for maize and sorghum in Africa†

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Abstract: Stem borers, comprising the larvae of a group of lepidopterous insects, and parasitic witchweeds, particularly Striga hermonthica and S asiatica, cause major yield losses in subsistence cereal production throughout sub-Saharan Africa. Studies are described that have led to the development of a ‘push-pull’ strategy for minimising stem borer damage to maize and sorghum. This involved the selection of plant species that could be employed as trap crops to attract colonisation away from the cereal plants, or as intercrops to repel the pests. The two most successful trap crop plants were Napier grass, Pennisetum purpureum, and Sudan grass, Sorghum sudanensis. The intercrop giving maximum repellent effect was molasses grass, Melinis minutiflora, but two legume species, silverleaf, Desmodium uncinatum, and greenleaf, D intortum, gave good results and had the added advantage of suppressing development of S hermonthica. In terms of stem borer control, the plant chemistry responsible involves release of attractant semiochemicals from the trap plants and repellent semiochemicals from the intercrops. With M minutiflora, parasitism of stem borers was also increased by certain chemicals repellent to ovipositing adults. The mechanism of striga control has not been fully elucidated, but allelopathic effects from the Desmodium species have been shown to involve stimulation of germination and interference with haustorial development. Significant beneficial effects have been obtained with the individual components of these push-pull strategies. However, the most robust crop-protection package is obtained when these components are combined. The trap crop and intercrop plants also provide valuable forage for cattle, often reared in association with subsistence cereal production. There has been considerable take-up of the system within the communities where farmer-managed trials have been carried out, particularly in the Trans Nzoia and Suba districts of Kenya, and the programme is set to expand throughout and beyond Kenya.

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1 INTRODUCTION

Stem borer and striga attack in subsistence cereal cultivation in sub-Saharan Africa can completely destroy the yield of crops such as maize and sorghum. The stem borers are larvae of lepidopterous insects (moths) comprising indigenous species such as the maize stalk borer, Busseola fusca (Full) (Noctuidae), and some non-indigenous species, for example the sorghum stem borer, Chilo partellus Swinh (Pyralidae). The adult moths locate suitable hosts and lay eggs, and the resulting larvae, in their early instars, shred the leaves before entering the stems of the plant, thereby causing yield losses and an increased susceptibility to wind lodging. Parasitic weeds, particularly the witchweeds, or strigas, Striga hermonthica Benth and S asiatica Kuntze (Scrophulariaceae), produce seeds that can remain dormant within the soil for up to 20 years. Both germination and haustorial initiation are stimulated by cues from the host plant. 1,2 This is followed by the development of haustoria and attachment to the host, which then provides nutrients for the parasite throughout its lifetime. 3 Although pesticides and herbicides can be used to alleviate these problems, complete control is seldom

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effected and, more importantly, they are too expensive for general use in these farming circumstances, which often involve small family farms of less than one hectare. Some direct treatments are available, for example use of fire ash against stem borers and hand-weeding against striga, but the favoured approach is to use an intercropping system. The mechanisms of these systems have generally been poorly researched, so that even when there is alleviation of pest or weed problems, maximisation of the effects has not been possible.

The objective of the present work was to investigate the diversity of species already growing or having been introduced into resource-poor regions in Africa, seeking plants that were highly attractive to adult stem borers, to serve as trap crops, and for plants that were repellent to stem borers and/or antagonistic to striga development, to use as intercrops. Since intercropping and mixed cropping generally are readily practised in these regions of Africa, farmer take-up was expected to be rapid, provided that robust methods for stem borer and striga control could be developed and demonstrated in procedures acceptable to these particular farming practices. Full experimental details will be published elsewhere (Khan ZR, Chiliswa P, Gohole L, Overholt WA, Kimani-Niogu SW, Mwendia C, Pickett JA, Smart LE, Wadhams LJ and Woodcock CM, in preparation).

2 EXPERIMENTAL

2.1 Selection of putative trap and intercrop plants

Triplicate small plots of hundreds of plant species were grown at the field station of the International Centre of Insect Physiology and Ecology (ICIPE) at Mbita Point, on the banks of Lake Victoria, Suba district, Kenya. The species were principally in the family Poaceae (= Graminae), ie grasses, but plants from other monocotyledonous families, eg the Typhaceae and Cyperaceae, and some legumes (Fabaceae), were also grown. After establishment, samples of the different plants were examined for attack by stem borers, particularly the indigenous B fusca and the non-indigenous C partellus, by splitting open the stems and counting the different stages of larvae present. Stem borer colonisation, which results from an initial choice by ovipositing adults, was assessed and the most attractive (putative trap crops) and least attractive (putative repellent intercrops) plant species were selected. Two poaceous plants attracted considerably more oviposition than maize. These were both forage crops, the Napier grass, Pennisetum purpureum Schumach, related to pearl millet, and the Sudan grass Sorghum sudanense Stapf, related to sorghum. Although Napier grass attracted more oviposition than maize, many of the larvae did not survive. However, Sudan grass allowed development of stem borers and also had a very high parasitisation rate, with 70–80% of the larvae being killed. Notably, the molasses grass, Melinis minutiflora Beauv, an indigenous poaceous plant which has been developed as a source of cattle forage throughout the world, particularly in South America, attracted no oviposition at all. M minutiflora is known locally to possess some anti-tick properties, causing ticks feeding on cattle to detach when the cattle are in contact with the grass.

Legumes are not attacked by cereal stem borers, so assessment of their activity was made in association with maize as the host plant, but out of these studies, two plants in the Desmodium genus, silverleaf, D uncinatum DC and greenleaf, D intortum (Mill) Urb, were shown to repel ovipositing stem borers.

2.2 The ‘push’ and ‘pull’ against stem borers

With putative ‘push’ and ‘pull’ plants having been selected in 1995, experimental trials began in 1996 at the Mbita Point field station in the Suba region and also in the Trans Nzoia region of Kenya, in collaboration with staff at the Kenyan Agricultural Research Institute (KARI) under the direction of Mr R Butaki. Initially, 30m × 30m plots of maize were grown either as monocultures or surrounded by a 5-m border of Napier or Sudan grass to act as a trap crop. Again, assessment was made by splitting the stems and counting the larvae present. In plots with a border of Napier grass, although there was considerably more oviposition and early larval development in the trap crop compared with the maize, only 20% of the larvae survived on the Napier grass, whereas 80% survived through to adults on the maize. This additional control effect was caused by production of sticky sap by Napier grass tissues in response to penetration by first- and second-instar stem borer larvae. Most of the larvae were trapped in the sticky fluid and were killed. With the Sudan grass border, the trap crop contained eight times as many larvae as the maize, and stem borer numbers within the maize were reduced to one-third compared with the maize monoculture (measured at the 12-week plant growth stage). In the following year, scientist-managed trials on small private farms in the Trans Nzoia region showed that the Napier grass trap crop system reliably gave significant improvements in yield of approximately 1 to 1.5 tonnes ha⁻¹. In 1998–9, farmer-managed trials with Napier grass and Sudan grass on poorly-yielding farms in the Trans Nzoia and Suba regions showed similar successes, with yield increases again of the order of 1–1.2 tonnes ha⁻¹. Separate studies in both regions, initially at experimental sites, moving into scientist-managed and then farmer-managed trials, demonstrated the effectiveness of intercropping with M minutiflora. For example, numbers of C partellus larvae found in maize stems were reduced from 80 in the monoculture plots to c five in plots having a row of M minutiflora planted between each row of maize (six replicate samples). The traditional intercrop, cowpea, Vigna sinensis (L) Savi (Fabaceae), only reduced numbers of larvae down to 45. Similar reductions were found for the other stem borer species. Although not as effective as M minutiflora plant which has been developed as a source of cattle forage throughout the world, particularly in South America, attracted no oviposition at all. M minutiflora is known locally to possess some anti-tick properties, causing ticks feeding on cattle to detach when the cattle are in contact with the grass.
flora, the two Desmodium species as intercrops also reduced stem borer damage, and the results were always significantly better than the maize monoculture or maize intercropped with other legumes, including cowpea. The planting rate for *M. minutiflora* with maize was subsequently reduced from a 1:1 intercrop:crop ratio to 1:3, with excellent results. Indeed, the effect was still statistically significantly different at a ratio of 1:10 (*P* < 0.05).

2.3 The semiochemistry of stem borer control by ‘push’ and ‘pull’ crops

Samples of host-plant volatiles, obtained by air entrainment onto a porous polymer (Porapak Q) and elution with solvent (hexane), were investigated by gas chromatography coupled-electroantennography (GC-EAG) on the antennae of stem borers, particularly *B. fusca*. GC peaks consistently associated with EAG activity were tentatively identified by GC coupled-mass spectrometry (GC-MS) and identity was confirmed using authentic samples. Six active compounds were identified (Fig 1): octanal (1), nonanal (2), naphthalene (3), 4-allylanisole (4), eugenol (5) and linalool (6). Behavioural tests, employing oviposition onto an artificial substrate treated with the individual compounds, demonstrated positive activity for all of these compounds. The discovery of naphthalene as an attractant for stem borers was initially surprising, since this compound is normally associated with mineral oil and coal tar chemistry, but the compound has now been identified as a semiochemical in other contexts.8,9

The next step was to investigate the volatiles produced by the intercrop plants. Coupled GC-EAG with volatiles from *M. minutiflora* showed a wide range of peaks associated with EAG activity. The specific objective here, however, was to identify active compounds not also found in the host-plant volatiles. A general hypothesis that we have developed during our work on insect pests is that non-hosts are recognised as inevitiable that compounds also produced by hosts will be present.10,11 In this case, the host cereal plants and the non-host *M. minutiflora* would be expected to have a number of volatiles in common as they are all members of the Poaceae. For *M. minutiflora*, five new peaks with EAG activity were identified, in addition to the attractant compounds and others normally produced by members of the Poaceae. These comprised (E)-β-octalone (7), α-terpinolene (8), β-caryophyllene (9), humulene (10) and (E)-4,8-dimethyl-1,3,7-nonatriene (11) (Fig 2). The ocimene and nonatriene had already been encountered as semiochemicals produced during damage to plants by herbivorous insects.12,13 It was considered likely that these compounds, being associated with a high level of stem borer colonisation and, in some circumstances, acting as foraging cues for parasitoids, would be repellent to ovipositing stem borers, and this was subsequently demonstrated in behavioural tests. Investigating the legume volatiles, it was shown that *D. uncinatum* also produced the ocimene and nonatriene, together with large amounts of other sesquiterpenes, including α-cedrene (12, Fig 2).

2.4 Exploiting parasitoids in stem borer control

As mentioned above, the pyralid moth pests such as *C. partellus* are not indigenous to Africa but have followed the cultivation of maize. In order to reduce damage by these exotic pests, the parasitoid *Cotesia flavipes* Cameron (Braconidae) has been successfully introduced by members of the Poaceae. These comprised *C. flavipes* (Cameron), can also reduce populations of the indigenous Noctuids such as *B. fusca*, and to a lesser extent the non-indigenous stem borer pests. Throughout the development of the trap and intercrop strategies described above, exploitation of these wasps has been attempted. However, in 1997, it was noted with some surprise that, although intercropping with *M. minutiflora* had reduced populations of stem borers in the maize, there were nevertheless still parasitoids ovipositing in these plots than in the maize monocultures (parasitised larvae in maize: monocrop 5.4%; intercropped with *M. minutiflora* 20.7%; *P* < 0.01).16 Returning to the chemistry identified as reducing stem borer attack, it was realised that compounds such as the nonatriene 11 might also be responsible for the increased parasitoid foraging. Indeed, when this compound was presented to *C. flavipes*, oviposition was reduced in the presence of the compound.17

![Figure 1](image1.png)

Figure 1. Volatile compounds from host plants having EAG activity with stem borers.

![Figure 2](image2.png)

Figure 2. Volatile compounds from *M. minutiflora* having EAG activity with stem borers.
sesamiae in a Y-tube olfactometer at a level similar to that found in the volatiles from M. minutiflora, it accounted for most of the attractiveness of the natural sample.\textsuperscript{16}

The importance of analytical techniques in quality control was exemplified by the observation that, as M. minutiflora seed was accumulated for more widespread field trials, the attractiveness of the material to C. sesamiae in the Y-tube olfactometer, and also the increased foraging in the intercrop plots, dropped to a level having no statistical significance. These plants had been cultivated exclusively at the Mbita Point field station.

However, when seed was acquired from the Thika region of Kenya, the M. minutiflora was again shown to be increasing parasitism by a factor of two, at a high level of statistical significance. Differential biosyntheses of foraging stimulants, including the nonatriene, are now under investigation. Nonetheless, without such scientific input, the robustness and reliability of these methods of pest control would be jeopardised.

Although the nonatriene \textsuperscript{11} and ocimene \textsuperscript{7} were also released by the Desmodium species and were responsible for their repellency to stem borers, there was no detectable increase in parasitism in the intercropped plots. It may be that other components produced by Desmodium, including the large amounts of \textsuperscript{12}z-cedrene (\textsuperscript{12}), are interfering with this effect. In the long term, this phenomenon may prove to be a useful discovery, as it is often necessary to repel parasitoids from situations where they could be harmed by other crop protection practices. For example, it could be valuable in deflecting ovipositing parasitoids from Napier grass, where the death of late-instar stem borer larvae could reduce developing populations of parasitoids. However, a new collection of Desmodium species has been established at the Mbita Point field station, and one cultivar of D. uncinatum has been found to produce enhanced amounts of the nonatriene and ocimene relative to other components such as \textsuperscript{12}z-cedrene. This cultivar may prove to be a more useful intercrop in terms of stem borer control, but its discovery indicates opportunities for further plant breeding, whether conventional or aided by molecular genetics. In addition, some of the Desmodium species having shrub-like habits or perennial cultivation cycles may be useful in protecting horticultural crops, where more robust stature and longevity could be required.

2.5 Striga control by intercropping with Desmodium species

In 1997, it was noticed that maize intercropped with D. uncinatum or D. intortum suffered far less striga infestation than maize in monoculture. These trials were repeated, comparing Desmodium species with plants recommended widely as intercropping solutions to striga problems, for example sun hemp, Crotalaria spp, soybean, Glycine max (L) Merr and cowpea, V. sinensis. With the conventional intercrops, either striga infestation was not significantly different from the maize monoculture, as with soybean, or the striga rating was only reduced by about 50%, as with sun hemp and cowpea. However, when maize was intercropped with a Desmodium species, the striga rating was reduced from 2–3 to 0.1 or less. At the same time, there was a statistically significant increase in maize yield of \(2\) tonnesha\(^{-1}\) \((P < 0.05)\).

The Desmodium species are nitrogen-fixing legumes and contribute to the nutrition of the crop. If allowed to grow uncontrolled, there can be competition with the crop, but this can easily be controlled by regular cutting. The mechanism by which these plants, as intercrops, reduce striga infestation so dramatically is now under investigation, there being clear evidence of allelopathic effects. There is already considerable knowledge of the nature of the stimuli, released from the roots of developing host plants, that cause germination, haustorial development and colonisation of crop plants and related wild species by striga.\textsuperscript{17–20} It is now imperative to identify the exact mechanisms by which Desmodium species interfere with striga development, to ensure that control measures based on these intercropping strategies are robust and reliable and with a view to exploitation in the longer term by means of plant molecular genetics. It can already be seen that D. uncinatum is producing germination stimulation cues in the rhizosphere, and also that there are compounds interfering with haustorial development and colonisation of the maize hosts, the chemistry of which is under investigation.

2.6 The full ‘push–pull’ strategy, or ‘vuta sukuma’

The strategy combining crop, trap crop and intercrop, whether to control stem borers alone or to reduce stem borer and striga infestation, has been highly successful, from the initial experimental trials through to scientist-managed farm trials and eventually to farmer-managed trials. The take-up has been enhanced by interactions with non-governmental organisations (NGOs) at Farmers’ Barazas and also by contributions from the media, particularly as a storyline in ‘Tembea na Majeera’, a serialised fictional radio programme depicting the daily lives of rural communities in East Africa. The approach is called in Kiswahili ‘vuta sukuma’, or pull–push, by the local farmers. Results are impressive. For example, using the full push–pull system with maize, D. uncinatum and Napier grass, in a trial on a relatively poorly yielding farm in the Suba district during the long rain season in 1998, control plots produced 1.8 tonnesha\(^{-1}\) compared with 3.0 tonnesha\(^{-1}\) for the treated plots, as a statistically significant increase \((P < 0.05)\). Similar results were obtained in 1999 in the Trans Nzoia region, where more productive farms also saw significant yield increases, ie 7–8 tonnesha\(^{-1}\) for the treated plots compared to 4–5 tonnesha\(^{-1}\) for control plots \((P < 0.05)\).

It has been our general principle that plants used to create push–pull pest management strategies must themselves have value for the communities involved.\textsuperscript{21}
In the work described here, the trap crops and intercrops can all be used as forage for livestock. Indeed, the luxuriant stands of Napier grass and Sudan grass have allowed the farmers to improve their cattle husbandry and many have increased the size of their herds, although it must be stressed that these, at most, may represent only ten or so individual animals. Scientists from KARI in Trans Nzoia, now headed by Dr C Mwendia, have also been able to demonstrate, at the Farmers’ Barazas, methods for producing cattle silage from the trap crops, which means that large amounts of forage produced during the growing season can be preserved for later use. In these regions, where zero grazing is the usual method for cattle husbandry, such forage is extremely important. Using an adapted panga with a curved end, it is also simple to harvest the *M. minutiflora* or *Desmodium* species intercrops for the same purpose.

Cost-benefit analysis, performed by socio-economists linked to Dr Mwendia’s research programmes, has shown returns to labour of over 2.2, with the maize monoculture returning less than 0.8 and even pesticide intervention systems less than 1.8.

3 THE FUTURE

The approach described here is set to expand into other regions of Kenya and more widely in East Africa, with discussions already taking place with Ethiopian, Ugandan and Tanzanian scientists and extension services. A pilot programme has been initiated in southern Africa, addressing stem borer and striga control in the arid and semi-arid areas of the Northern Province of South Africa. Each region has, in addition to varying climatic conditions and use of alternative cultivars, some differences in crops that must be taken into account, and considerable experience has been gained in this aspect by the pilot study in southern Africa. Whereas maize is the main crop in the farming systems in Kenya, sorghum, pearl millet and maize are planted in southern Africa. Habitat management options in this region are affected by low rainfall, the limited extent to which cattle are kept and the fact that the cattle are largely free-grazing. Whilst the increased planting of trap crops is justified by their significant roles as animal feed in East Africa, this is not the case in South Africa and the ‘added on’ value of trap crops will have to be found in soil fertility (erosion) management or novel uses of trap crops. However, wherever these approaches are developed for the specific needs of local farming practices and communities, it is essential that the scientific basis of the modified systems should be completely elucidated, otherwise there will be a drift from effectiveness and justifiable dissatisfaction on the part of the practising farmers. There has already been considerable technology transfer between the collaborating laboratories in the UK and Nairobi and the field stations at Mbita Point and in Kitale. Every effort will be made to ensure that technology transfer follows the incorporation of these practices into other regions of Africa and, it is hoped, the world more widely.

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REFERENCES

14 Overholt WA, Ngi-Song AJ, Omwega CO, Kimani-Njogu SW, Mbapila J, Sallam MN and Ofomata V, A review of the introduction and establishment of *Cotesia flavipes* Cameron (*Hymenoptera: Braconidae*) in East Africa for biological control of *Sorghum bicolor*.


